A Geoconservation perspective on the trace fossil record

associated with the end – Ordovician mass extinction and glaciation in the Welsh Basin

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“The earth is utterly broken down, the earth is clean dissolved, the earth is moved exceedingly”

Isaiah, 19. James 1st Bible

“Nothing in the world is permanent or lasting;

everything is changing and momentary and unpredictable”

The Teachings of Buddha, Bukkyo Dendo Kyokai, 1984

“We are all the sons and daughters of catastrophe”

Richard Fortey, Survivors: Nature's Indestructible Creatures, BBC, 2012

Declaration

"The material being presented for examination is my own work and has not been submitted for an award of this or another HEI except in minor particulars which are explicitly noted in the body of the thesis. Where research pertaining to the thesis was undertaken collaboratively, the nature and extent of my individual contribution has been made explicit."

Signed

Keith Henry Nicholls

March 2019

Acknowledgements

I would like to offer my warmest thanks to my Internal Supervisory Team at the University of Chester, Professor Cynthia Burek & Dr Lottie Hosie.

In addition I have benefited from the knowledge and advice from two external advisors. They are Professor JR Davies MBE, formerly British Geological Survey, now Aberystwyth University, and Dr Kate Riddington, formerly of the Grosvenor Museum, Chester; and latterly of the Lapworth Museum, Birmingham. Jerry Davies in particular has been hugely supportive throughout and has been a convivial occasional companion in the field.

Throughout my studies I have had wide ranging and interesting discussions with many individuals who have all been generous with their time, and offered tangible support. Particular mention must be made to Thijs Vanderbrouke (Ghent University), Duncan McIlroy (Memorial, Newfoundland), Bill Fitches, Jonathan Wilkins (XRD analyses), Liam Herringshaw, Brad Cramer, Michael Crouch (formerly East Anglia, now Manchester), Jan Zalasevicz (Leicester); Matt and Dan at the Sedgwick Museum, Cambridge; Jacqui Malpas and all the members of the NEWRIGS group.

Jonathan Wilkins, and all the members of the North Wales Geology Association, members of the Geological Society of London (North West Regional Group), the North Staffordshire G.A. and the Mid Wales Geology Club have listened with interest to my developing thesis. Alex Finlay of Chemostrat has helped with discussions with respect to the Dobb's Linn GSSP. Particular mention must be made to two individuals who offered me generous support in the very earliest stages of my research; both Richard Twitchett and Simon Braddy must be acknowledged – without their interest in the trace fossils I was finding at Llangrannog, long before taking up formal studies, this piece of work would not have have gone any further than being a passing interest. Staff at the National Museum of Wales, in particular Cindy Howells who arranged my visit to see (and even hold!) the type specimen of Murchison's *Nereites cambrensis*. CGG (in particular Lisa Buckley) for the use of their polarising microscope with camera facility (Hirnant Limestone slides).

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It has been a particular pleasure to renew an old friendship with Alastair Welbon of VNG Norge who, along with his family, were wonderful hosts for an extremely rewarding weekend looking at the O/S boundary sections in Oslofjord.

The first seeds of interest in geology and palaeontology were sown by my primary school teacher in St Thomas Infants and Juniors, Swansea: Mrs Moira Mounce. As well as teaching me about Vesuvius, Mrs Mounce brought a seriously ill seven year old a Children's Encyclopaedia on “Dinosaurs”. Whilst nearly fifty years later, my interests have ended up with creatures of a somewhat smaller scale, that book was clearly the start of this process.

Since first picking up a copy of “Wonderful Life”, Stephen Jay Gould's published musings on various aspects of Natural History have been constant sources of pleasure, and an inspiration to me. If at times my writing becomes a little florid, it is perhaps because I have read too much of Gould's work, and find his writing both eloquent, and informative. His was a standard I can only aspire to reach.

In his essay “The Lying Stones of Marrakesh” Gould makes the following statement:

> *“So scientists go to work for competing pharmaceutical or computer companies, make monumental salaries, but cannot choose their topics of research or publish their work.”*

I have been entirely spared the need to direct my studies at anything other than what I have been interested in, by the generous legacies of my mother in law, “Sadie” McDonaugh, and my parents “Jack” and Mary Nicholls. Since this thesis is in essence about the ability of generations to pass on their genetic legacy to their children, it does appear appropriate to dedicate this work to “our Parents”.

This version of the thesis has been considerably revised following an initial submission in the spring of 2017. The current version is a much more focussed document than the original, and I offer my warmest thanks to my internal and external examiners who clearly took their responsibilities seriously, and reviewed my work thoroughly. Irrespective of whether or not this submission is deemed adequate by my examiners, it is clearly much improved.

Finally thanks must be offered to the vagaries of Mother Earth herself, who over the majority of the course of my research ensured that beach sand levels in Cardigan Bay were particularly low. Had the level of sand in Cilborth Beach Llangrannog been as we see it in 2018, opportunity to see and inspect the trace fossil assemblage there would have been extremely limited.

No doubt I have missed naming some individuals who have assisted my studies – apologies to all if that is the case. In any event, I do wish to state that any errors, omissions or failings that are present in this thesis, are mine and mine alone, those involved in assisting me could not have done any more.

This thesis is a contribution toward IGCP591 “The Early to Middle Palaeozoic Revolution”.

Abstract

In this thesis I have illustrated the value of our geological heritage and geodiversity by focussing on a particular detailed aspect of the geological and palaeontological record, i.e. the trace fossil record associated with the end Ordovician (Hirnantian) global glaciation and extinction episode.

The major elements of this work that are new are:

- a significantly improved understanding of the nature of the soft sediment deformation, and in particular the role of "debrites" as basal landslide decollements in the Lower Palaozic Llangrannog rock succession of West Wales,
- a much more detailed description of the trace fossil ichnocoenose present in the Llangrannog succession than has previously been published
- an improved understanding of the nature of the ecological perturbation associated with the Hirnantian (Late Ordovician) Glacial "ice-house", and the apparent role of an opportunistic soft body fauna in filling ecological niches vacated as a consequence of the associated extinction.
- Considerable thought has been given to the question of how to value abiotic nature, and it is argued that the methods of conservation valuation associated with "Geosystem services" and in particular "Natural Capital" hold considerable potential for the Geoconservation community to engage with the public and with policy makers.
- As a direct result of this research, two formal proposals have been put forward for new RIGS sites, together with a new geological SSSI.

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Chapter 1:

Introduction

Please take me back my Mother the Land
Embrace me like Mother and Child
The message goes out from your children who shout
Only visitors and there for a while

Phill Moncrief

The worth of fossils simply cannot be measured in dollars

Stephen Jay Gould

Introduction

1.0 Aims of this thesis

This thesis is intended to focus on the trace fossil record and associated sedimentary features and body fossil content of the Hirnantian rocks in the Welsh Basin, and the need for geoconservation of sites that inform our understanding of a period of profound change of climate and faunal turnover.

This thesis will describe and comment on the local aspects of glacially induced sea-level change (glacio-eustasy), trace fossil (ichnological) and palaeontological events, and their relationship with what is generally considered to be the second most significant global mass extinction in the Phanerozoic.

It is intended to compare and contrast the successions associated with the greater marine palaeo-depths of the Llangrannog area (Ceredigion) situated in the west of the Welsh Basin (Primary Study Area (i) and a shallow water environment; the Hirnant (Bala) area, situated in the east of the Welsh Basin (Primary Study Area (ii)). These present linked, but profoundly different aspects of the response of the sedimentary, geochemical, and most notably faunal context of the Hirnantian palaeo-environment.

The most important element of the scientific research undertaken is the detailed ichnotaxonomy of the Llangrannog trace fossil assemblage (or ichnocoenose) which is described in detail for the first time in the scientific literature.

1.1 Structure of thesis

Following this short introductory chapter will be chapters describing:

i. the history of research into trace fossils in the Welsh Basin

ii. the geological setting of the Hirnantian rocks in the Welsh Basin, within the broader temporal context of the Welsh Basin, and global climate change

iii. a detailed description of the Llangrannog succession (Primary Study Area (i))

iv. a formal ichnotaxonomy of the Llangrannog trace fossil assemblage

v. the palaeoecological significance of the Llangrannog ichnofauna, and comparison with other relevant successions within and without the Welsh Basin

vi. a description of the Cwm Hirnant (Bala) succession (Primary Study Area(ii)), and comparison with other relevant successions within the Welsh Basin

vii. a final chapter which describes the trace fossil assemblage within a geoconservation perspective and offers conclusions with respect to the need for active conservation of some of the sites described, and the argument is made that the trace fossil assemblage at Llangrannog merits consideration as a potential Site of Special Scientific Interest (SSSI).

viii. whilst this thesis concentrates on the rock record associated with two critical locations (Llangrannog and Cwm Hirnant (Bala)) geological processes are not discretely confined in either space or time, and I have benefitted from studying (albeit in less detail) successions from older (earlier Ordovician) and younger (Silurian) rocks elsewhere in the Welsh Basin and contemporaneous rocks from outside this area. Where relevant, descriptions of these locations are presented as illustrative greyed out inset boxes.

1.2 Global Hirnantian Stratigraphy

The Hirnantian Stage (HS) is defined by Global Boundary Stratotypes and Points (GSSPs) at Wangjiawan in China, and Dob's Linn in Scotland (see Inset Box 1). These GSSPs are currently defined at 443.4Ma and 445.2Ma respectively. Despite the points of temporal definition being elsewhere, the name itself is derived from the original type location in Cwm Hirnant (*sensu lato*) near Bala described by Bancroft (1933), and formally established as the last stage of the Ordovician in 2006 (Chen, Rong et al. 2006).

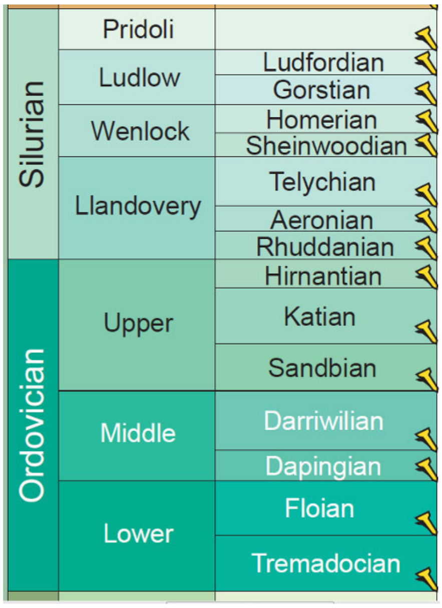

Figure 1.1: Current stratigraphic framework for the Ordovician and Silurian Series showing chronostratigraphic correlation (right hand column) and the location of fully defined global stratigraphic points. The Hirnantian Stage is represented by a 1.8 million-year interval between defined GSSPs in China and Scotland. Data from current published Stratigraphic Chart (Cohen, Finney et al. 2013).

The HS is further sub-divided by defined graptolite biozones comprising the lattermost *anceps* zone, and the subsequent *extraordinarius* and *persculptus* zones. The succeeding Llandovery Stage, and therefore the defined base of the Silurian, is associated with the first appearance datum (FAD) of the zonal graptolites of the *acuminatus* graptolite biozone.

Inset Box 1 Dob's Linn, Scotland, Moffat, Scottish Borders (NGR NT196158)

This is an extensively studied outcrop with hugely significant historical associations (Lapworth 1879; Elles and Wood 1918). The rocks record a major change in the oceanic palaeo-environment, with relatively oxic pale grey Hartfell Shales (Ordovician, Hirnantian) overlain by the darker grey (latest Hirnantian / earliest Silurian, Llandovery) Birkhill Shales. The Hartfell Shales are typically pale grey thinly planar bedded, in places thinly laminated silty mudstones, with, for the most part rare or sporadic graptolites. Occasional thin bands of darker (more Birkhill Shales-like) do have graptolites, preserved in pyrite. The Birkhill Shales are typically dark grey, richly fossiliferous shaly mudstones with occasional thin bentonitic clay bands, representing distal volcanic fall out.

The detail of the stratigraphy has been the subject of considerable debate (Williams 1983; Underwood, Crowley, Marshall and Brenchley 1997), but the current defined position of the Ordovician – Silurian boundary GSSP (Chen, Rong et al. 2006; Rong, Melchin, Willams, Koren and Verniers 2008) relates to the incoming of the graptolite species *Akidograptus ascensus*.

The section has been, and remains, an attractive location for recent and ongoing research (Verniers and Vandenbroucke 2006; Finlay, Selby and Gröcke 2010).

1.3 Geoconservation Principles

Without prematurely introducing matters to be discussed at length in the final chapter relating to Geoconservation it is necessary to establish a number of key definitions which will be referred to from time to time throughout the body of this thesis.

Table 1.1 Key Geoconservation definitions

Item	Definition
RIGS Site	Regionally Important geological / geomorphological site
SSSI	Site of Special Scientific Interest - The concept of the SSSI was introduced into UK legislation with the enactment of the National Parks and Access to the Countryside Act, 1949; and was developed further with the Wildlife and Countryside Act, 1981. These matters in Wales were devolved to the Welsh Assembly by the Government of Wales Act, 2006.
GSSP	Global Boundary Stratotype and Point – Globally recognised standard section with agreed palaeontological occurrences (typically first appearance datum (FAD) that are used to define stratigraphic horizons
GCR Site	Geoconservation Review Site

1.4 Key Locations

1.4.1 Llangrannog

The coastline between Llangrannog Beach (SN 310 542) and Traeth yr Ynys Lochtyn (SN 317 550) is a designated RIGS site with the following formal citation:

"*This coastal section is a regionally important site for several reasons. The Lower Palaeozoic sedimentary rocks exposed here, namely the Llangranog Formation and overlying Gaerglwyd Formation, span the late Ordovician - early Silurian boundary, a major time break in the stratigraphic column. Excellent exposure provides opportunities to obtain detailed information about these formations that can be used when following them and the Ordovician-Silurian boundary inland where exposure is generally poor. The Traeth Bach Member, the upper part of the Llangranog Formation, shows spectacular examples of folds and faults produced by slumping and other gravity-driven movements of the sediment before lithification. Dark mudstones in the sequence commonly contain well preserved graptolites that may be used to date the rocks. In parts of the Gaerglwyd Formation there are particularly clear examples of septarian concretions, unusual pillow-sized carbonate-rich bodies produced by chemical processes during lithification of the sediment. The rugged cliff line is a major scenic attraction of the Cardigan Bay coast, as recognized by the National Trust which owns parts of the RIGS.*"

In addition, the coastline is protected under a SSSI designation relating to the Aberarth – Carreg Wylan SSSI. However, the geological designation for this SSSI relates to Quaternary sections at Mwnt and Poppit (to the south of the study area) and to Caledonian structural features (Traeth Penbryn immediately south of the study area; and Mwnt), that is to say the significance of the remarkable soft sediment deformation, and accompanying trace fossil assemblage are not recognised.

Figure 1.2: Primary Study Area (i) – Llangrannog and district

The understanding of the local stratigraphy has moved on since that RIGS citation was written and a comparative stratigraphic column which identifies common, but now defunct lithostratigraphic formation names in inverted commas is given in Table 1.1. The right-hand column indicates the lithostratigraphy that is recognised in this thesis.

1.4.2 Bala

Cwm Hirnant ("Valley of the long stream" in Welsh) is a north trending glaciated valley located south east of the town of Bala. The study area is a 2km by 2km square centred on SH 949 300 as shown in Figure 1.3, as shown below:

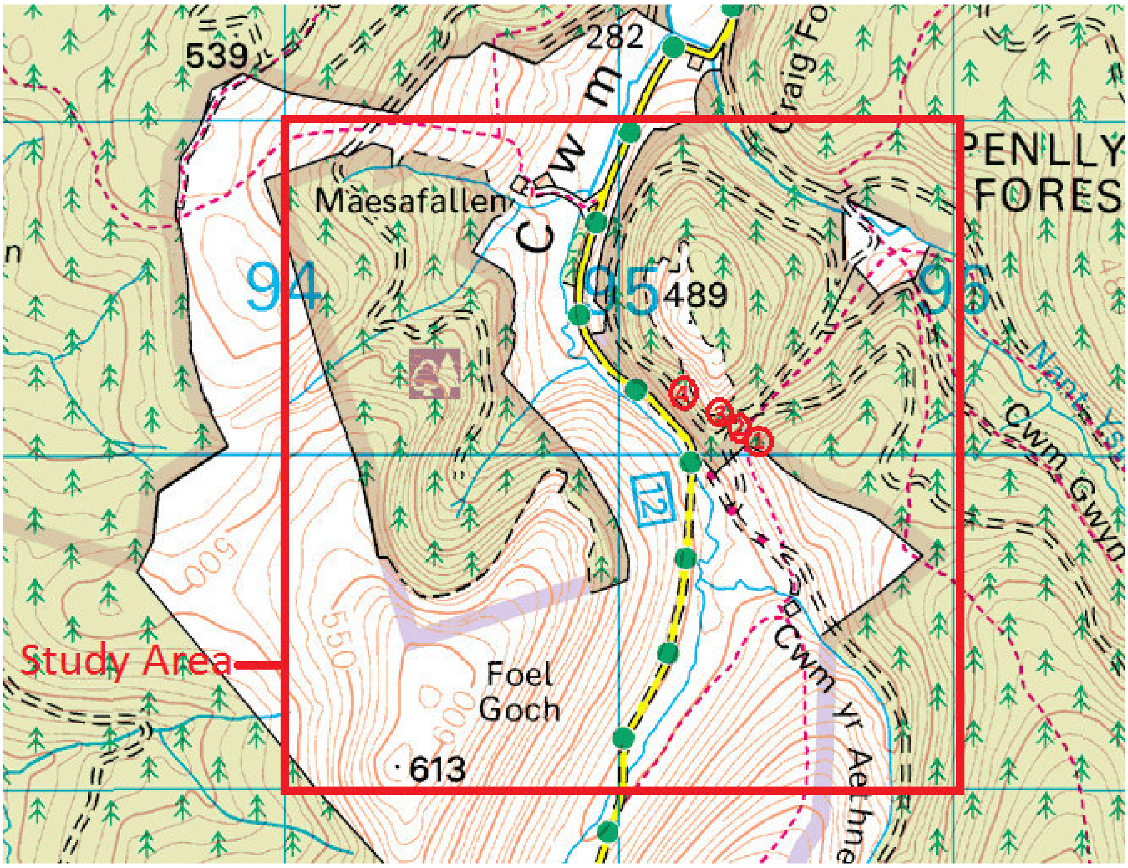

Figure 1.3 Primary Study Area (ii) – Cwm Hirnant

As described previously this is Bancroft's original type area, and it is also the original location for the definition of the first diagnostic Hirnantian macro-faunal marker assemblage, the "*Hirnantia* Fauna" (Semple 1965). A small quarry located at SH951296 is a formally designated SSSI associated with the establishment of the globally recognised "Hirnantia Fauna", the globally recognised stage name for the upper most Ordovician (Hirnantian) and the two eponymous, diagnostic brachiopod species *Hirnantia sagittifera* and *Eostropheodonta hirnantensis*

There has been a long history of research in this area, and Tables 1.2 and 1.3 summarise earlier lithostratigraphic schemes for Llangrannog and the Bala District, and compares them with the lithostratigraphy used in this thesis.

1.5 Ethical Statement

Prior to detailing the fieldwork undertaken it is appropriate to detail the ethical status of the research work undertaken. Collection of specimens (Appendix 1) has been limited where appropriate to fragments of loose material, or to material that is already exposed and subject to natural loss or degradation through weathering and slope instability. When working at designated SSSI sites (for example Cwm Hirnant and Dobb's Linn, Scotland) appropriate permission for very limited and strictly controlled sampling has been obtained from Natural Resources Wales (formerly Environment Agency, Wales) and Scottish Natural Heritage, as appropriate.

At the time of commencement of the study it was not considered necessary to seek formal departmental ethical approval for the work.

On completion of this study it is intended to offer all the collected material to an appropriate institution for permanent curation. I am currently pursuing their placement with the National Museum of Wales.

1.6 Copyright statement

Unless noted otherwise all photographic images used in this thesis have been taken by the author, and rights over all further reproduction are asserted.

1.7 Spelling of the "Llangrannog" place name

The place name "Llangrannog" (Parish of Crannog) is frequently spelt in its' Anglicised form as "Llangranog". The Anglicised version has been commonly used in the technical literature, and used as a formation name in previous stratigraphic work. Where I have referred to the location I have chosen to use the correct Welsh spelling of "Llangrannog", but where I am quoting others, or using the "Llangranog Formation" (*sensu* Ankatell / Fortey) I have retained the original as published version.

Table 1.3

Baseline Stratigraphy				Cwm Hirnant and surrounding area				
				Ramsey	**Elles**	**Bassett et al**	**Fortey et al**	**Nicholls (herein)**
Global	**Regional (UK)**	**Stage**	**Graptolite Zonation**	**1866**	**1922**	**1966**	**2000**	**2018**
Llandovery		**Rhuddanian**	***acuminatus***	"Llandovery Rocks"	"Cwm yr Aethnen Shales"	"Cwm yr Aethnen Mudstones"	"Cwm yr Aethen (sic) Shales"	**Cwm yr Aethnen Mudstone Formation**
Hirnantian	**Ashgill**	**Hirnantian**	***persculptus***	"Hirnant Limestone"	"Hirnant Grits and Mudstones"	"Foel y Ddinas Mudstones" [1]	"Foel y Ddinas Mudstones" [2]	**absent** **Hirnant Limestone Member**
			extraordinarius		"Foel y Ddinas Mudstones"			**Foel y Ddinas Mudstone Formation**
Katian		**Rawtheyan**	***anceps***	"Caradoc"	"Moel-fryn Mudstones"	"Moelfryn Mudstones"	"Moelfryn Mudstones" [3]	**Moelfryn Mudstone Formation**
		Cautleyan			"Rhiwlas Limestone and Mudstone"			
		Pusgillian	***complanatus***					
	Caradoc (pars)	**Onnian**	***linearis***					

Notes

[1] Hirnant Limestone and Calettwr Quartzite Members omitted for clarity

[2] Hirnant Limestone Member omitted for clarity

[3] Rhiwlas Limestone Member omitted for clarity

Inverted comma notation indicates discarded nomenclature

Table 1.3
Comparative Lithostratigraphy - Bala District

References

Ramsey, A.C. (1866)

Elles, G.L. (1922)

Bassett, D. A., H. B. Whittington and A. Williams (1966)

Fortey, R. A., D. A. T. Harper,et al. (2000)

Table 1.2

Global	Local	Regional (UK)	Graptolite Zonation	Lind Hendriks 1926	Ankatell 1987		Fortey et al 2000	Challends et al 2009	Davies et al 2009	Nicholls (herein) 2018
				Llangranog and surrounding area						
Llandovery		Rhuddanian	*acuminatus*		"Gaerglwyd Formation"		"Gaerglwyd Formation"		Cwmere Formation	Cwmere Formation
Hirnantian	Ashgill	Hirnantian	*persculptus*	"Orange weathering shales"				"Cwmere Formation"		
				"Pyritous Mudstone"					Mottled Mudstone Member	Mottled Mudstone Member
			extraordinarius	*"Ribbony Beds"*	"Llangranog Formation"	"Traeth Bach Member"	"Llangranog Formation"	"Yr Allt Formation"	Brynglas Formation [1]	Brynglas Formation [2]
				"Massive grits - thin grits-gritty mudstones"		"Morfa Member"			Drosgol Formation	Drosgol Formation
			anceps	*"Gnarled Grits"*		"Sarnau Member"				
Katian		Rawtheyan		*"Truncatus Beds"*		"Carreg y ty Member"		"Nantmel Mudstone Formation"	Nantmel Mudstone Formation	Nantmel Mudstone Formation
		Cautleyan				"Penbryn Member"				
					"Tresaith Formation"		"Tresaith Formation"			
		Pusgillian	*complanatus*				"Black Shales"			
	Caradoc	Onnian	*linearis*				"Poppit Formation"	"Cwm yr Eglwys Mudstone Formation"		

Notes

[1] Basal Pencerrigtwnion Member omitted for clarity

[2] Basal Pencerrigtwnion Member not recognised - horizon with evidence of downcutting / channelization

Inverted comma notation indicates discarded nomenclature

Table 1.2
Comparative lithostratigraphy - Llangranog District

References

Lind Hendriks. D.M. (1926)
Anketell, J. M. (1987)
Fortey, R. A., D. A. T. Harper, et al. (2000)
Challands, T.J., H.A. Armstrong, et al. (2009).
Davies, J.R., R. A. Waters, et al. (2009)

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Chapter 2:

Literature Review: Trace fossils in the Welsh Basin

"Geology reveals to us the extraordinary fact, and without its aid the fact could never have been known, that as the globe passed from one condition to another, whole races of animals perished, and were succeeded by others with organisations adapted to the altered state of our planet"

Sir Roderick Impey Murchison,1839

Literature Review: Trace fossils in the Welsh Basin

2.0 The Welsh Basin:

The Welsh Basin can be loosely defined as comprising all the sedimentary strata, recording a marine sedimentary succession of Cambrian, Ordovician and Silurian rocks which outcrop throughout much of South West, Mid and North Wales, including parts of the border country of Shropshire and Herefordshire. On the Geological Map of Wales and the Welsh Borderland below (Figure 2.1, NERC 2009) the Welsh Basin sediments are defined by the pale green, light and mid purple colours associated with the Cambrian, Ordovician and Silurian (excluding Old Red Sandstone) rocks.

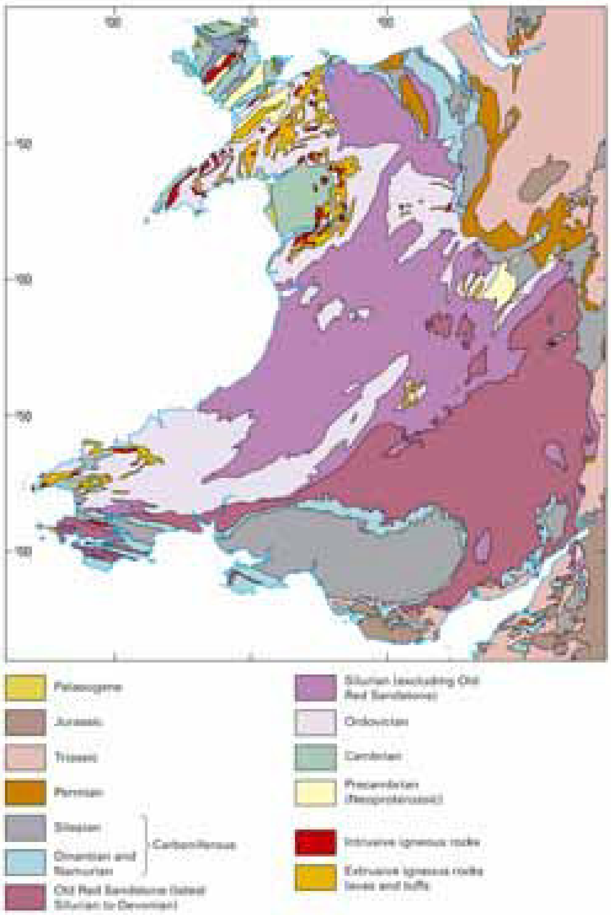


Figure 2.1 Outline bedrock geological map of Wales and the Welsh Borders (NERC 2009)

Howells (2007) describes how the "structural grain" established in the Pre-Cambrian basement helped define the location of a subsidence prone basinal sequence bounded between the Midland Platform (along the Church Stretton, Pontesford –Linley and Tywi Faults) and the Irish Sea Horst (along the Menai Straits Fault Zone). In these very broad terms the geological history spans from lower Cambrian strata (Comley Series) to

Silurian (Pridoli) strata. Within this succession there are extensive deposits of volcanic rocks mostly of Ordovician age, most obvious at outcrop in and around Snowdonia. There are also significant hiatuses and non-sequences within the succession, some of which record significant angular unconformity, others which do not.

These rocks were deposited on an older basement sequence of metamorphosed sedimentary and granitoid rocks of Late Precambrian age, now preserved as remnant outliers around the perimeter of the defined Welsh Basin, in the Malverns (*circa* 680-670Ma). Strachan R.A., R.D., Nance, et al 1996), The Long Mynd (*circa* 590-575Ma. Toghill 1990) and in Llŷn and Ynys Môn (620-585Ma. McIlroy and Horak 2006). The oldest rocks of the Welsh Basin sequence itself, as defined above, are the so called "Harlech Grits" and associated strata, at outcrop in the north east corner of Wales around the eponymous town of Harlech.

The Cambrian sedimentary deposits are overlain by a mixed predominantly silici-clastic succession of Ordovician sedimentary deposits. These include the first widespread development of limestones and relatively low energy typically fine-grained mudstones and shales (slates when metamorphosed) of the Silurian. Clastic shelf deposits are common in the Welsh Borders. The still water fine grained Silurian strata are locally interspersed with channelized coarse-grained flow deposits. Marine deposition within the Welsh Basin waned in the mid to late Silurian with the gradual shallowing of the seas, and the influx of terrestrial sedimentation in latest Ludlow and Pridoli times associated with the onset of the Acadian / Caledonian Orogeny (Howells, 2007). This is generally taken to mark the end of "Welsh Basin" sedimentation.

Associated with the Ordovician rocks in particular, are extensive volcanic rocks, comprising both intrusive stocks, dykes and sills, as well as associated extrusive rocks including basalts and tuffs. It is notable that the volcanism, at least on a regional basis, appears to have shut down during Hirnantian times. Field relations in Snowdonia do not show any intrusive igneous intrusive contacts that cut Hirnantian strata, confirming the cessation of active volcanism, at least on a regional basis.

To the east of the Welsh Basin was a structural high associated with the Midland / Avalon Platform. It is generally accepted that lineaments such as the Tywi Lineament, and the Bala Fault were active in controlling sedimentation (Howells 2007) with the Welsh Basin receiving sediments derived from these active structural features.

2.1 Work on trace fossils in the Nineteenth Century:

The study of what we have come to know as "ichnology" i.e. the study of trace fossils in their own right, was not part of the nineteenth century geologist's repertoire. This was not a function of trace fossils not having been found, or indeed even described, but rather a misunderstanding prevalent amongst many of the pre-eminent workers of the time as to the origin as traces, rather than being external casts of unknown phyla. Some of the very earliest work in the Welsh Basin records features associated with trace fossils, sometimes in the case of "*annelid burrows*" they are recognised as trace fossils, but on other occasions they are identified and described as body fossils, and were often placed in a "catch–all" sub-division of the memoirs of the time under "*incertae sedis*" or misclassified as having affinities to algae and described as "*Fucoids*" (see discussion in Osgood 1970, pages 286-289). The names of trace fossils still record this supposed association with algae by the presence of the suffix "*...phycus*" in the etymology of the ichnogenera.

A typical example of this method of working is presented in Murchison's key work that established the Silurian System. Murchison recorded the presence of such "fucoids" in what he termed "*Caradoc Sandstone, or in the beds of passage between that formation and the Wenlock Shale*", and specifically describes *Nereites cambrensis, Nereites sedgwickii, Myrianites macleayii* and *Nemertites ollivantii.* The "*Caradoc Sandstone*" and "*Wenlock Shale*" to Murchison would equate with what we would now consider to be Katian (Late Ordovician) to Wenlock (Early Silurian) strata. Murchison records all these occurring at Lampeter, Carmarthenshire "*In the schistose building-stone of that place, in which they were found by the Rev. A. Ollivant, Professor of Llampeter College*".

The type specimen of *N. cambrensis* was viewed and photographed (Figure 2.2) during a visit to the National Museum of Wales, in Cardiff. The type specimen of *N. sedgwicki* (Figure 2.3) thought to be held in the collection of the Sedgwick Museum was not available for study and may have been mislaid.

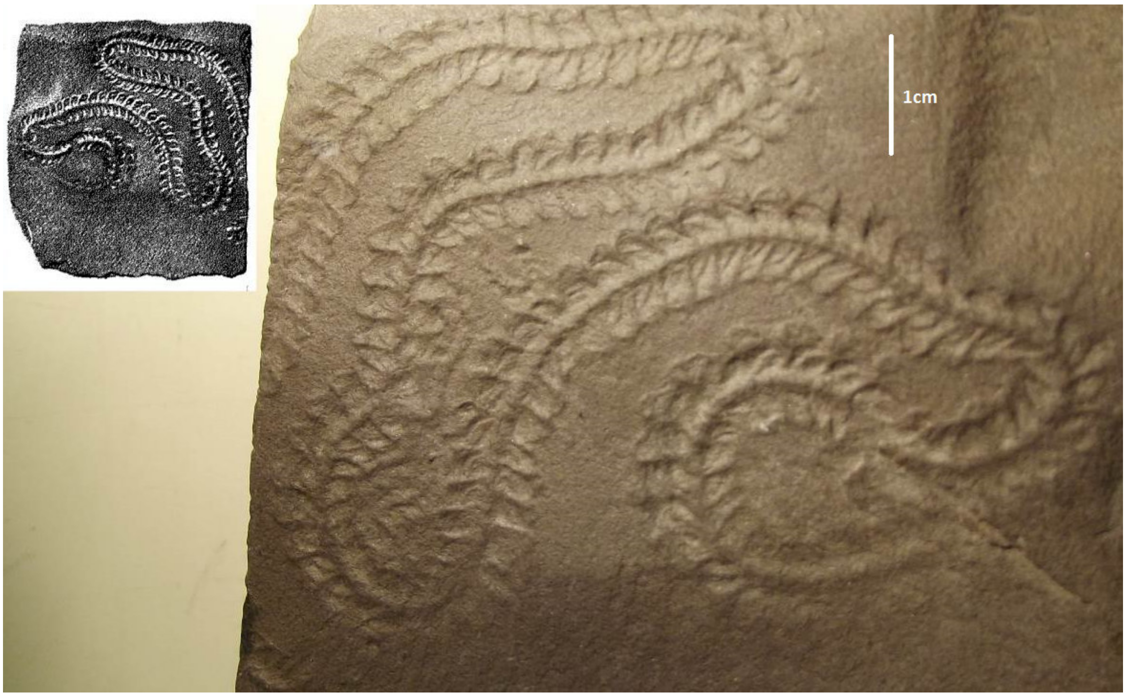


Figure 2.2: ***Nereites cambrensis*** **original as figured specimen inset (Murchison, 1839) and a close up image of the type specimen held at the National Museum of Wales, Cardiff.**

The index card held with the type specimen records as follows:

"NARIETIES (sic) *CAMBRENSIS*
Ordovician – Llandeilo Sil. Llandovery
Locality: Lampeter"

The left / right inversion of the drawing with respect to the image is thought to be an artefact of the drawing reproduction method.

Murchison identified two of these traces as actually representing body fossils of the extant family of polychaete worms *Nereidina,* typically represented by large crawling invertebrates with four eyes, four pairs of peristomial cirri, and a pair of jaws (Ruppert and Barnes 1994). In his description of the *N. sedgwicki* type specimen Murchison came close to recognising the origin of the fossils as traces, although did not take the intellectual step of identifying the whole of the trace as being of mechanical origin, produced by the action of the animal, rather than being a true fossil, formed following passive taphonomic preservation.

> *"The impression now under consideration was clearly that of an animal, as will appear by the figure, where the worm has evidently, before coiling, with difficulty trailed itself along in the mud, in a way, which any one accustomed to collect these Annelida will at once recognise."*

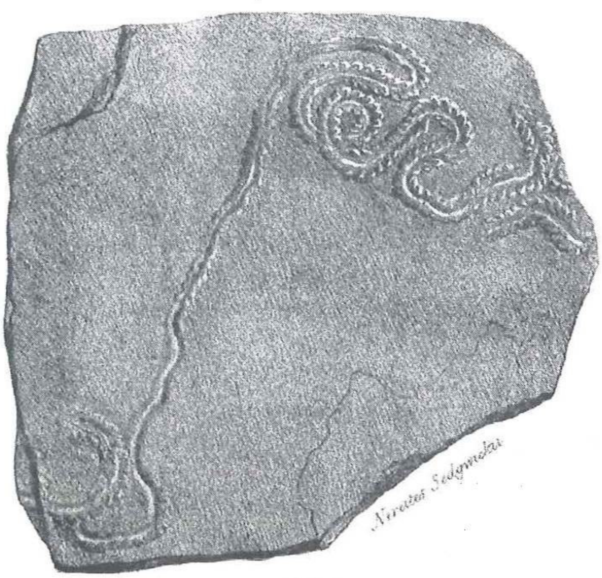


Figure 2.3: *Nereites sedgwicki* original as figured specimen (Murchison, 1839), Scale not recorded but presumably the trace is of the order of 1cm width

Murchison appears to have made a similar error in his descriptions of two trace fossils of the ichnogenera *Helminthoida* which he identifies as *Myrianites macleayii* (Figure 2.3) and *Nemertites ollivanti* (Figure 2.4).

Figure 2.4:
Myrianites macleayii **original as figured specimen (Murchison, 1839), scale not recorded.**

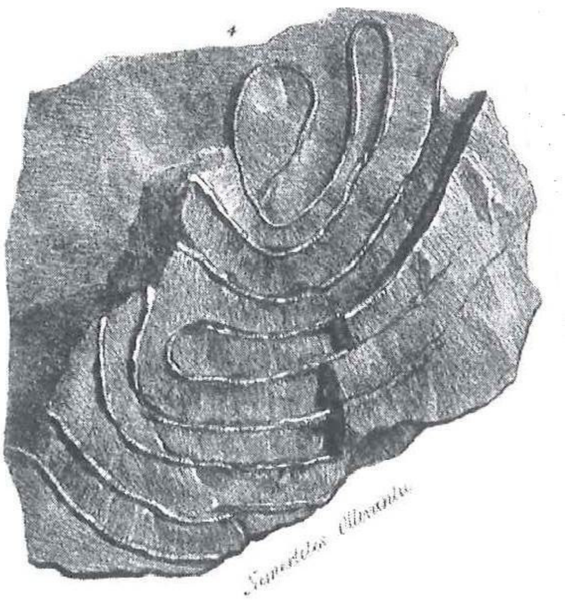


Figure 2.5:
Nemertites ollivanti **original as figured specimen (Murchison, 1839), scale not recorded.**

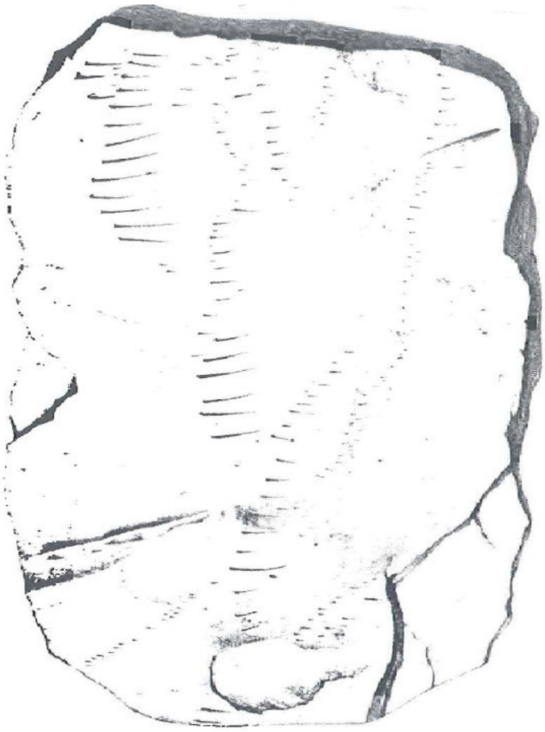


Figure 2.6
Tracks associated with *Hymenocaris vermicauda* (Plate 1 in Salter's Appendix to Ramsay's Memoir), scale not recorded.

Trace fossils form a substantial part of the body of work produced as the Memoir of the Geological Survey of Great Britain (Ramsay 1866) with its palaeontological Appendix by J.W. Salter (Salter 1866). The traces are generally described as "Annelids".

Plate 1 in Salter's Appendix (Figure 2.6) presents a full-page sketch of what are annotated as "Tracks, probably made by the *Hymenocaris vermicauda* – Tremadoc North Wales" from the "Lingula Beds". These appear to be traces with an affinity to what we now would attribute the ichnogeneric name "*Dimorphichnus*" which are generally thought to be ascribed to the "striding" behaviour of trilobites.

Other trace fossils figured by Salter include *Cruziana semiplicata*, "*Annelide Burrows*" (various types including one identified as *Chondrites*), and "*Worm burrows* (*Scolithus*)". It is again notable that Salter, although identifying and describing these traces, does not fully identify them as such – with the following description of *Cruziana* apposite in this regard:

> *"A group of large and remarkable fossils, doubtfully referred by its discoverers first to Articulata, and then (with less probability) to plants. The specimens consist of more or less elongated and convex impressions, deeply furrowed down the middle, sometimes quite bilobed, and from the median line the sides are plaited in an oblique direction, so as to roughly imitate leaf venation. They are of considerable geological interest, very similar forms occurring in the Silurian*

rocks of Spain, Normandy, Britain and North and South America. In Europe they are, as far as yet known, Lower Silurian; and are all of an elongated form, and occur in sandy strata. In the new continent they are of a shorter and rounded shape. Sir E. Logan has brought fine specimens from the calciferous sandstones of Canada, and in New York and the Western States the genus occurs under the form of C. (Rysophycus or Fucoides) biloba Vanuxem, as high as the Clinton Group or the upper part of the Middle Silurian. ***These broader forms have been ingeniously referred by Prof. Dawson to the burrows of crustacean (trilobites); but I think they cannot belong to them.****"* (Emphasis KHN)

It is however apparent that Salter was on the verge of recognising the traces (at least *Cruziana semiplicata* and *Chondrites*) as being related to burrowing activity since in their specific description he states:

"From the mode in which the matted surfaces of Cruziana and the cylindrical bodies called Chondrites occur on the ripple marked faces of the beds, it is most probable that the latter are the tubular contents of worm tubes, or rather the rejectementa from their bodies as they passed through the silty layers. It is by no means certain that Cruziana too, though at present generally arranged among fucoids or sea-weeds, may not have been a worm tube or burrow filled up also, and I shall here adopt this opinion"

2.2 Work in the early Twentieth Century

The nineteenth century work in the Welsh Basin described above is associated with the great dispute between Sedgwick and Murchison in connection with the placement of the boundary between Sedgwick's "Cambrian" strata and Murchison's "Silurian". Resolution of that dispute is recorded in 1890 by Sedgwick's biographers (Clark and Hughes 1890) as follows:

"Now comes a curious sequel to our story. A proposal has been made to take all Sedgwick's Arenig and Bala Beds, and Murchison's Llandeilo and Caradoc, and constitute not Upper Cambrian, not Lower Silurian, but Ordovician, with a view to putting an end to controversy! One shell is given to Sedgwick, the other to Murchison, but who gets the oyster?"

This proposal had been put forward by Charles Lapworth (1842-1920) working primarily with the common colonial hemichordate fossils, graptolites. In 1879 he put forward his "tri-partite" division of the lower Palaeozoic strata (Lapworth 1879) which subsequently (although not without further dispute and controversy, as described by Woodcock 2000), eventually formed part of the accepted framework of Lower Palaeozoic stratigraphy. The utility and accuracy of Lapworth's work however had far reaching consequences with respect to the further development of research in the Welsh Basin, with the early years of the twentieth century being dominated by, in general, macro-faunal stratigraphy, and in particular the detailed study of graptolites by Lapworth's students including Ethel

Shakespear (nee Wood, 1871-1946) and Gertrude Elles 1872-1960 (Elles 1909; Elles and Wood 1918; Elles 1922; Elles 1939). The intervening system is what we now recognise as the Ordovician.

Contemporaneous work in the Llandovery region was undertaken by O.T. Jones (1878-1967) of Manchester and latterly Cambridge Universities, resulting in his two publications describing the geology of his southern and northern research areas (Jones 1925; Jones 1949). Much of this work informed the development of the geosyncline paradigm (Jones 1938), which dominated thinking in the area for a considerable number of years thereafter.

The long lists of fauna recovered and described from these rocks at this time, reflect the preponderance of stratigraphical research methods based on macro-fauna. There is little mention (if any) of the presence of trace fossils. This seems strange in comparison with the earlier period of work, but presumably, rather than indicating their absence from these rocks, may reflect a lack of trust in their utility as stratigraphic tools. However, the following brief aside is made in Jones' paper of 1912:

> *"The only other district concerning which information is forthcoming is the coast south of Llangranog. The Dicellograptus-bearing mudstones are succeeded by a considerable thickness of grey grits, these are followed by 200 to 300 feet of dark-blue, flaggy, sandy shales and mudstones, which are exposed on the steep slopes south of Traeth Bach (three quarters of a mile south-west of Llangranog). I have searched these shales for fossils, but without success. They appear to be followed conformably by dark shales with thin bands of dark-grey grits* ***showing curious markings like annelid trails****, and closely resembling in their lithological characters the beds at the base of the Aberystwyth Grits farther north."(Jones 1912).* (Emphasis KHN)

2.3 Work in the late Twentieth Century

Adolf Seilacher (1925-2014) established two fundamental principles of ichnological research:

- classification schemes built on ethological principles, (Seilacher 1953), and
- bathymetric control on trace fossil occurrences – hence establishing the ichnofacies concept (Seilacher 1967)

With the realisation that ichnological principles could be useful in palaeoenvironmental analysis, and subsequently in sequence stratigraphy, interest in trace fossils waxed considerably, with key review documents published relating to *Chondrites* (Simpson 1956), *Trace Fossils of the Cincinatti Area* (Osgood 1970), and *Trace Fossil Concepts* (Basan, Chamberlain et al. 1978). Perhaps the key publication in returning the field of ichnology to the palaeontological mainstream, was the posthumous revision of Hantzschel's Part W of the Treatise on Invertebrate Paleontology (Hantzschel 1975). Inclusion of trace fossils alongside "Problematica" was an unfortunate but perhaps an inevitable result of the association with "*incertae sedis*" of previous generations. Bound in as Appendix 2 to this thesis, is a CD copy of an Excel spreadsheet which summarises the data published in Hantzschel (1975), in terms of the range of occurrence of the ichnogenera listed.

Stratigraphic nomenclature as used at that time is substantially different from current stratigraphic practice. The resolution of the published ranges is also somewhat lower than would normally be considered ideal – but it seems reasonable to correlate the current Hirnantian / Llandovery transition as being broadly equivalent to the Richmondian / Alexandrian transition of then US practice.

There is an intriguing collapse in apparent ichnogeneric diversity over this period from an ichnogenera count of 53 to 27. This apparent ichnogeneric "extinction" episode however must be treated with some caution. Global palaeoecology of the time is generally associated with ecological recovery following extinction (Armstrong 1996), and transgression following the Hirnantian eustatically controlled regression (Brenchley and Newall 1980). It may be the case therefore that the apparent absence of trace fossils reflects, at least in part, a period of particularly poor preservation potential, rather than the absence of benthic activity.

The following table is a list of the ichnogenera cited by Hantzschel occurring within the general stratigraphic range associated with the Hirnantian / Richmondian Stage:

Table 2.1: Hantzschel's (1975) Ichnogenera listing – global Hirnantian / Richmondian

Ichnogenera
Amphorichnus, Arthraria, Arthrophycus, Arthropodichnus, Asteriacites, Bergaueria, Bifasiculus, Chondrites, Conichnus, Corophiodes, Crossopodia, Cruziana, Curvolithus, Daedalus, Dictyodora, Didymaulichnus, Dimorphichnus, Diplichinites, Diplocraterion, Fraena, Fucosopsis, Helminthopsis, Lockeia, Lophoctenium, Merostomichnites, Monocraterion, Neonerietes, Nereites, Ormathichnus, Palaeophycus, Palaeodictyon, Phycodes, Phycosiphon, Phyllodocites, Phytopsis, Planolites, Protovirgularia, Rauffella, Rhizocorralium, Rusophycus, Sabellarites, Saerichnites, Scalarituba, Scolicia, Skolithos, Teichichnus, Teratichnus, Tigillites, Trachomatichnus, Treptichnus, Trichophycus, Tylichnus, Zoophycos (53 No ichnogenera)

The reason that it is appropriate to consider the 1975 Treatise Part W (see also Appendix 2) under a discussion of the Welsh Basin is that it drew heavily on a 1970 publication of Conference Proceedings held at the University of Liverpool (Crimes and Harper 1970). In particular, a key paper in that publication was Crimes' comparative study of Lower Palaeozoic trace fossils in Wales and Ireland (Crimes 1970).

Crimes listed ichnogenera from the overlying "Lower Silurian" (s.l.) Aberystwyth Grits Formation. The following table is derived from his Figure 4 (p. 110).

Table 2.2: Crimes ichnogenera listing (*Nereites* community - Turbidite sequences, Aberystwyth Grits)

Age	Lithology (Location)	Listing
Early Silurian	**Aberystwyth Grits**	***Nereites,*** ***Dictyodora,*** ***Paleodictyon*** ***Chondrites*** "Graptolite Drag Marks" *

*as tool marks, not associated with the work of an animal, these would normally be excluded from ichnogenera listings

Between 1976 and 1979 research was undertaken at Cambridge University by Philip M Magor, and his collection is held at the Sedgwick Museum, Cambridge. This collection includes a number of trace fossils collected from the "Upper Ordovician" of the Welsh Basin. The cataloguing process has erroneously established the location of a number of his samples (WS6 and WS 8 through 12) as being from "*Llangremog*", whereas the original labels indicate these to be from "*Llangrannog*". E-mail correspondence with Phillip Magor has confirmed that his research was never written up, nor was it published.. (Magor 2012 pers. comm.).

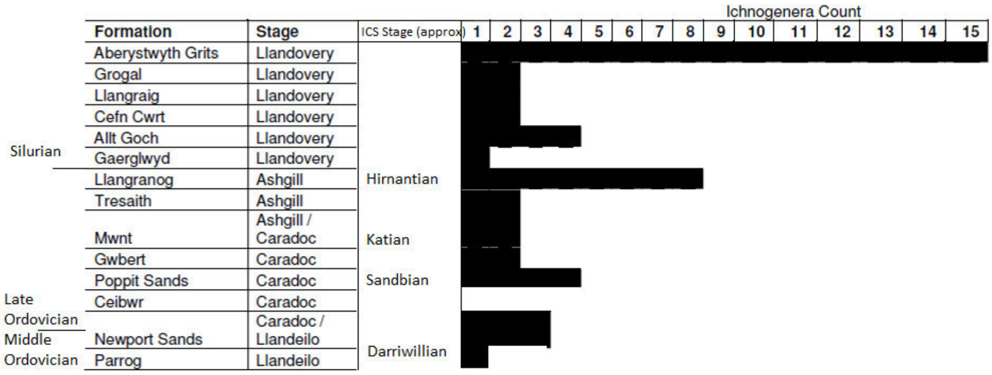
This work was contemporary with work undertaken by Pat Brenchley (1936-2011) and his associates at Liverpool University, including a detailed assessment of Caradoc (i.e. Sandbian) trace fossils from the Berwyn Hills by Ron Pickerill (Pickerill 1977). This work cast doubt on the established "ichnofacies" based on bathymetry (Seilacher 1967), rather suggesting that primary control is afforded by substrate and ecology.

In 1987 a conference involving both the British Sedimentological Research and Tectonic Studies Groups was held at Aberystwyth, and the proceedings were published in a Thematic Edition of the Geological Journal (Fitches and Woodcock 1987). Therein a paper by Ankatell on the succession and structure in South Central Wales is notable as in establishing a fourfold division of the "Ashgill" and Llandovery succession, reference is made to what was termed the "Llangranog Formation" (broadly equivalent to the Bryngias Formation) as follows:

> *"Although locally displaying a **rich assemblage of trace fossils**, the formation is devoid of diagnostic fauna"*(Anketell 1987). (Emphasis KHN).

Further detailed work looking at trace fossils in the Welsh Basin was published by McCann (1990,1993). McCann attempted to assess long term temporal change in the overall ichnofaunal record.

The rocks were considered to be deep water lower Palaeozoic "flysch" type marine sediments found in the relatively deeper water succession of the Welsh Basin. McCann (1990) records the presence of 15 ichnogenera in rocks ranging from Llandeilo (Soudleyan – Latest Middle Ordovician) through Llandovery (lowermost Silurian) strata. These reflect a somewhat surprising distribution through this interval, as shown in Figure 2.7, with peak Late Ordovician ichnofaunal diversity (8 ichnogenera) recorded in the Hirnantian "Llangranog Formation" (recently reassigned as Brynglas / Drosgol Formations (Davies, Waters et al. 2009)).



List of ichnotaxa recorded by McCann (1990)

Deep sea ichnogenera

Acanthoraphe, Belorhaphe, Circulichnus, Cosmorhaphe, Desmograpton, Fucusopsis, Fustiglyphus, Glockerichnus, Gyrophyllites, Halymenidium, Helicolithus, Helicorhaphe, Helminthoida, Laevicyclus, Lophoctenium, Megagrapton, Nereites, Oldhamia, Palaeodictyon, Palaeomeandron, Protopalaeodictyon, Spirophycus, Spirorhaphe, Strobilorhaphe, Sublorenzinia, Subphyllochorda, Taphrelminthopsis, Unarites, Yakutatia

"Facies crossing" ichnogenera

Alcyonidiopsis, Arenicolites, Bifasciculus, Buthotrepsis, Chondrites, Diplichinites, Diplocraterion, Gordia, Granularia, Gyrochorte, Helminthopsis, Mamilichnus, Muensteria, Neonereites, Ophiomorpha, Palaeophycus, Peleypodichnus, Phycodes, Planolites, Rhizocorrallium, Sabularia, Saerichnites, Scalituba, Scolicia, Skolithos, Taenidium, Thalassinoides, Zoophycos.

Figure 2.7: Graphical representation of ichnodiversity through time in the Ordovician Welsh Basin as reported by McCann (1990).

McCann makes a number of interesting remarks with regard to the various potential biases apparent in using ichnofaunal diversity as a proxy for biological diversity. The potential for a single biological species to generate multiple ichnospecies (*Rusophycus, Cruziana* and *Diplichinites* all relate to trilobite activity for example) is significant. The ichnofaunal diversity is also seen to be highly facies dependent. It is also notable that the Aberystwyth Grits Formation (more latterly defined as a Group) is significantly thicker than the majority of formations with which it is compared, and this may also, at least in part, lead to the comparative "ichnodiversity" recognised.

The trace fossils of the Silurian Aberystwyth Grits Group were further described by Crimes and Crossley, recording the presence of 25 ichnogenera (Table 2.3) and concluding that ichnofaunal diversity through time suggested a gradual increase in faunal diversity through the lower Palaeozoic in deep marine environments (Crimes and Crossley 1991).

Table 2.3

Ichnogenera of the Aberystwyth Grits Group (after Crimes and Crossley, 1991)

Asteriacites, Bergaueria, Chondrites, Cochlichnus, Cosmorhaphe, Glockerichnus, Gordia, Helicolithus, Helminthopsis, Helminthoida, Hormosiroidea, Lorenzinia, Megagrapton, Monomorphichnus, Neonereites, Nereites, Palaeophycus, Paleodictyon, Planolites, Protopaleodictyon, Spirorhaphe, Spirophycus, Squamodictyon, Subphyllochorda, Taphrhelminthopsis

This argument was subsequently developed further by Orr who identified a progressive colonisation of the deep marine environment, and particularly the *Nereities* ichnofacies in post-Cambrian strata (Orr 2001).

2.4 Recent and current work

In a widely available field guide published by the National Museum of Wales (Woodcock and Bassett 1993), a description is given of rocks in the Machynlleth / Llanidloes area (Leng and Cave 1993). One of the excursions describes the outcrop at Cardiganshire Slate Quarry where the waning of the Hirnantian Glaciation is linked to consequent transgressive pulses, and the establishment of a *persculptus* graptolite fauna immediately below the Mottled Mudstone Member at the base of the Cwmere Formation, the mottling resulting from bioturbation.

Publication of Bromley's text book "*Trace Fossils, Biology and Taphonomy*" (Bromley 1990) and the "*Palaeobiology: A synthesis*" Treatise (Briggs and Crowther 1990) serve to mark the establishment of ichnology as a mature topic in its own right. The Treatise included sections describing methods relating to the role that study of ichnology has in respect of:

- palaeoecology (Farrow 1990; Pemberton, Frey et al. 1990)
- taxonomy (Kelly 1990).

This period also saw the introduction of systematic approaches to fieldwork, and classification techniques (Trewin 1994). A Geological Society Special Publication (Bosence and Allinson 1995) included two significant review articles which detailed:

- the onshore – offshore trends displayed by trace fossils (i.e. updating Seilacher's "ichno-bathymetry") (Bottjer, Cambell et al. 1995)
- the critical role of the substrate in determining trace fossil taphonomy, and preservation potential (Goldring 1995).

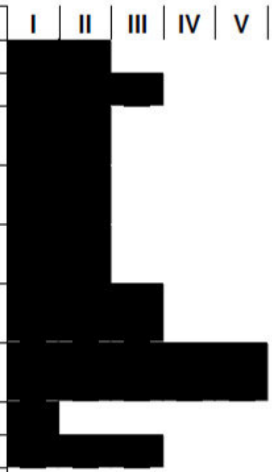
This has been followed by two major text books which consolidate the topic, these being Seilacher's "*Trace Fossil Analysis*" (Seilacher 2007) and (more recently) Buatois and Gabriela Mangano's "*Ichnology: organism – substrate interactions in space and time"* (Buatois and Gabriela Mángano 2011). This ichnological "modern synthesis" has seen the growth of numerical methods in ichnological research (Dattilo 1996; Goldring, Taylor et al. 2005), and the application of trace fossil studies in sequence stratigraphy (Rodríguez-Tovar, Uchman et al. 2010; Pearson, Mángano et al. 2012).

A specific area of study that has seen significant growth is the use of trace fossils as proxies for palaeoenvironment during mass extinction episodes. However, this work has, to date at least, been dominated by workers interested in the end-Permian, end-Triassic and end-Cretaceous (K/T event) mass extinction crises (see Appendix 3 for the justification of this assertion), which are not the subject of this research.

Specific studies relating to the end Ordovician (Hirnantian) extinction in the Welsh Basin have been limited, although there is growing interest as a consequence of the realisation that trace fossils represent a significant opportunity to study palaeoenvironmental change and palaeoecology. In the revised British Regional Geology Guide to Wales (Howells 2007) the presence of an undefined but apparently "rich" trace fossil assemblage in the "Llangranog Formation" is recorded. However, the relationship of this formation with the separately described "Yr Allt Formation" is unclear. The BGS Sheet Explanation (Sheet 194 Llangranog) published in 2006 details the use of burrow mottling / bioturbation as a proxy for palaeo-environmental change (Davies, Sheppard et al. 2006).

Herringshaw and Davies (2008) attempted to assess the ichnofaunal record associated with the Hirnantian and immediately pre- and post-dating rocks in the original "Type" Llandovery rocks of southwest Wales. Formal ichnofabric indices (Droser and Bottjer 1986) were utilised to classify the bioturbation observed in rocks ranging from Rawtheyan through to Rhuddanian. Figure 2.7 shows the results of this exercise:

Unit	Age	Ichnofabric Index
Crychan Formation	Rhuddanian	II
Bronydd Formation		II-III
Garth House Formation	Hirnantian	II
Cwm Clyd Sandstone Formation		II
Cwmcrynglyn Formation		I-II
Ciliau Formation		II-III
Cribarth Formation	Rawtheyan	V
Nantmel Formation		I
Tridwr Formation		II-III



for graphical purposes mid range indices (eg I-II) are shown at the top of the range (ie II)

Figure 2.8: Graphical representation of variation of Ichnofabric Index through Rawtheyan to Rhuddanian time in the shallow marine sedimentary deposits of South West Wales (after Herringshaw and Davies, 2008)

A fall in the overall Ichnofabric Index can be identified within the Hirnantian. However this is much less apparent if the extensively bioturbated Cribarth Formation is excluded as an outlier. Within the Rawtheyan strata the low Ichnofabric Index associated with the Nantmel Formation (finely laminated mudstone) is significant, although somewhat at odds with the widespread burrow mottling present in this formation in coastal outcrop. Throughout the remaining Rawtheyan strata *Chondrites* is recorded as the primary ichnotaxon. The Hirnantian ichnofaunal assemblage comprises:

• sand filled vertical burrows (unnamed, possibly *Skolithos*?)
• horizontal burrows (unnamed, possibly *Planolites*?)
• unnamed fugichnial (escape) burrows.

The overlying Rhuddanian strata are recorded to include *Cochlichnus, Helminthopsis, Planolites,* and *Diplocraterion*. In broad ichnodiversity terms therefore Herringshaw and Davies infer a steady expansion of diversity from the Rawtheyan (*Chondrites* only) through the Hirnantian (3 ichnotaxa implied) to the Rhuddanian (4 ichnotaxa recorded).

Challands, Armstrong, et al (2009), describe the outcome of investigations in the far west of the Welsh Basin, primarily south of Llangrannog (ie in strata slightly older than Hirnantian) and record the presence of the following ichnofauna:

Thalassinoides
Chondrites
Planolites

The positive identification of *Thalassinoides* is one of the earliest stratigraphic occurrences in the literature (although see also Droser and Bottjer, 1989, quoted in Wright and Cherns, 2016). This trace fossil only has a post Triassic range as listed in the Treatise Part W. Extensive Late Ordovician occurrences have also been recorded from Laurentia however (Jin, Harper et al. 2011), where they are taken to be diagnostic of stable equatorial conditions rather than the temperate latitudes at the time of the onset of global cooling. Nevertheless, Challands, Armstrong et al (2009) argue convincingly that the trace fossil record is a coherent proxy for changes in local palaeooceanography, specifically the chemistry associated with redox characteristics. In his original Ph.D. thesis Challands (2008) identifies a coeval apparent disappearance of infaunal burrowers in both the shallow water, shelf environment of the Welsh Basin (Ciliau and Cwmcringlyn Formations); and the basinal sediments of the Drosgol and Brynglas Formations.

Recent work by the British Geological Survey has formally established the Mottled Mudstone Member which occurs close to the Ordovician / Silurian boundary (*persculptus* zone, latest Hirnantian) as a (presumed contemporaneous) basin wide marker horizon (Schofield, Davies et al. 2008). Similarly, the absence / presence of burrow mottling is now being used as a proxy for establishing likely redox characteristics of the substrate over much of the Welsh Basin outcrop ((Davies, Waters et al. 2009 (b); Davies, Waters et al. 2009(a)).

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Chapter 3

Geological Setting and Context

We are in a state of profound scientific ignorance about the Earth and what science we do have is as yet hardly applicable for the solution of our environmental problems

James Lovelock (2000)

Geological Setting and Context

The Hirnantian rocks (latest Ordovician) of the Welsh Basin reflect events that occurred approximately 444 million years ago. This study is concerned with the primary sedimentological processes which acted on the sediments, at the time they were laid down and immediately thereafter, i.e. in advance of lithification and significant diagenesis.

The Hirnantian Stage is generally accepted to be associated with:

- A major global glaciation and "ice-house" period (Xu, 1984; Hambrey 1985; Blanpied, Deynoux, et al. 2000; Ghienne 2003; Brenchley, Marshall, et al. 2006; Loi, Ghienne, et al 2010; Delabroye and Vecoli 2010; Finnegan, Bergmann et al. 2011; Ghavidel-syooki, Alvaro, Popov and Suyakova 2011).

- The second most significant apparent macro-faunal mass extinction episode of the Phanerozoic (Sepkowski, 1982; Sepkowski, 1986; Sheehan and Coorough, 1990; Robertson, Brenchley and Owen 1991; Finney, Berry et al. 1999; Sheehan, 2001; Rasmussen and Harper, 2011; Finnegan, Heim, Peters and Fischer 2012); although see McGhee, Sheehan, Bottjer and Droser (2004) for an alternative view point with respect to the rank of the Hirnantian Extinction event.

- A significant carbon isotope excursion (The "HICE") and associated geochemical anomalies and markers (Xiaofeng and Zhifang (1990); Long 1993; Marshall, Brenchley et al. 1997; Kaljo, Hints, Martma and Nolvak 2001; Underwood, Crowley, et al 1997; Ainsaar, Kaljo, et al 2010; Fan, Peng and Melchin 2009; Marshall, Brenchley, et al. 1997; Brenchley, Carden, et al. 2003; Melchin and Holmden 2006; Schmitz and Bergstrom 2007; LaPorte, Holmden, et al 2009; Yan, Chen, et al 2009; Hannigan, Brookfield and Basu 2010; Finlay, Selby and Grocke 2010; Holmden Panchuk, and Finney 2012; Holmden, Mitchell, et al 2013, Jones, Creel and Rios 2016).

- The presence of a particular faunal assemblage (the *Hirnantia* Fauna) typified by the presence of brachiopods such as *Eostropheodonta hirnantensis, Hirnantia sagittifera, Dalmanella* and the trilobite species *Mucronapsis mucronata* (Wright, 1968; Rong, Xu and Harper 2002; Cocks and Cooper, 2004; Mergl 2011; Zhan, Liu, Liang and Li, 2011).

In assessing the nature of any marine succession it is necessary to understand the (sometimes complex) interplay that is occurring between climatic variability, local and global tectonism and the biosphere. It is also necessary to separate the effects that are "local" in context – reflecting "weather" rather than "climate", "an earthquake" rather than "tectonism", and local "extirpation" rather than "extinction" – from those that are genuinely global events.

In this case there is significant evidence that the early Hirnantian Stage witnessed a major glacio-eustatically controlled sea level fall, resulting in global regressive sequences in the rock record. This global event can be recognised in the rocks of the Welsh Basin, but has not, to date at least, been widely discussed in the literature. The Welsh Basin sediments were laid down (at a latitude of approximately 30^0S) in an ensialic basin environment, situated on the western seaboard of a micro-continent known as Avalonia. The ocean to the west of Avalonia is generally given the name of the Iapetus Ocean. The sea level fall occurred as a consequence of the locking up on land of significant quantities of global freshwater, as snow and ice, on a south polar continental landmass (Gondwana).

There is ongoing debate as the length of the Hirnantian Glacial Episode. Many early workers tended to suggest an intense but relatively short-lived glacial episode of perhaps a million years duration (Marshall, Brenchley et al. 1997; Ghienne 2003). Recent workers however are proposing a much longer period of cold climate extending below the *extraordinarius* graptolite zone (Finnegan, Bergmann et al. 2011; Harper, Hammarlund et al. 2013). Observations of the onset of soft sediment instability and of pervasive relatively oxic environments seen in the Nantmel Formation (pale grey colouration, widespread burrow mottling) throughout mid Wales (see Site Visit Report 10 "Traeth Penbryn", Appendix 1) confirm the onset of changes in palaeo ocean-chemistry in rocks thought to be of *anceps* biozone age.

The Hirnantian Outcrop in the Welsh Basin is shown in Figure 3.1. It can be seen that the outcrop generally thins from the relatively deep-water facies in the west, to a very thin outcrop in the more littoral facies of the eastern part of the basin. Further east the Hirnantian Stage is represented by a significant hiatus and associated unconformity (such as is seen at outcrop beside the River Onny at NGR SO425853).

The locations studied in detail in this thesis are seen to represent two extremes of the Hirnantian succession in the basin therefore, the western deep-water succession at Llangrannog, and a shallow marine succession at Cwm Hirnant. Fig 3.1 shows the major continental configuration of the globe at 425Ma and 458Ma with the Hirnantian Stage at circa 444Ma a mid-point between these two images. The major elements of ongoing tectonics in this part of the globe during this period were the closure of the Tornquist Sea between the Avalonian micro-plate and Baltica which lay to the north (red Arrow 1 on the Figure); and the subsequent closure of the Iapetus Ocean between Baltica / Avalonia and Laurentia (red Arrow 2 on the Figure).

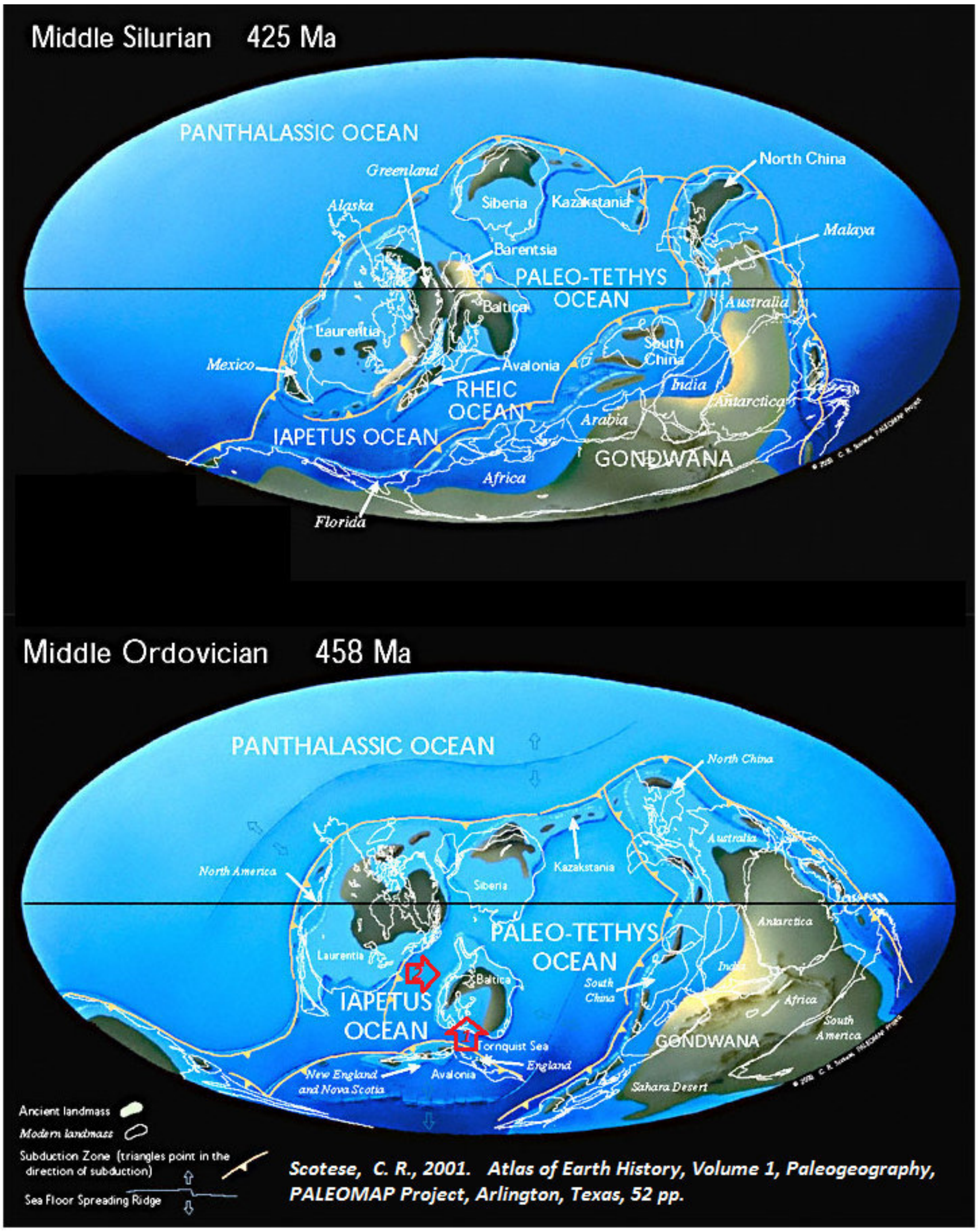

Figure 3.1 Major Continental Configuration at 458Ma (below) and 425Ma (above). (Scotese 2001)

The back-arc volcanism associated with subduction to the north of Avalonia is represented by the extensive volcanic suite of rocks present in Snowdonia. This volcanism however had become relatively quiescent with the end of subduction of oceanic crust between Avalonia and Baltica, and the onset of continent / continent tectonics, and the so called "Shelvian Phase" (Toghill 1992, McKerrow, Mac Niocaill and Dewey 2000, see Figure 3.3). Examination of both extrusive and intrusive contact relationships throughout North and Mid Wales reveal no evidence of any Hirnantian igneous activity in the area, supporting the apparent cessation of bark arc volcanism by (at the latest) close of the Rawtheyan Stage.

Subsequent closure of the Iapetus Ocean led to continent / continent collision associated with the Acadian phase of the Caledonian Orogen and the inversion of the sedimentary succession in the Welsh Basin, with the long period of marine sedimentation being replaced in late Silurian / Devonian times by the terrestrial influenced sedimentation associated with the "Old Red Sandstone" facies rocks present in parts of South Wales, and in marine sequences in Devon.

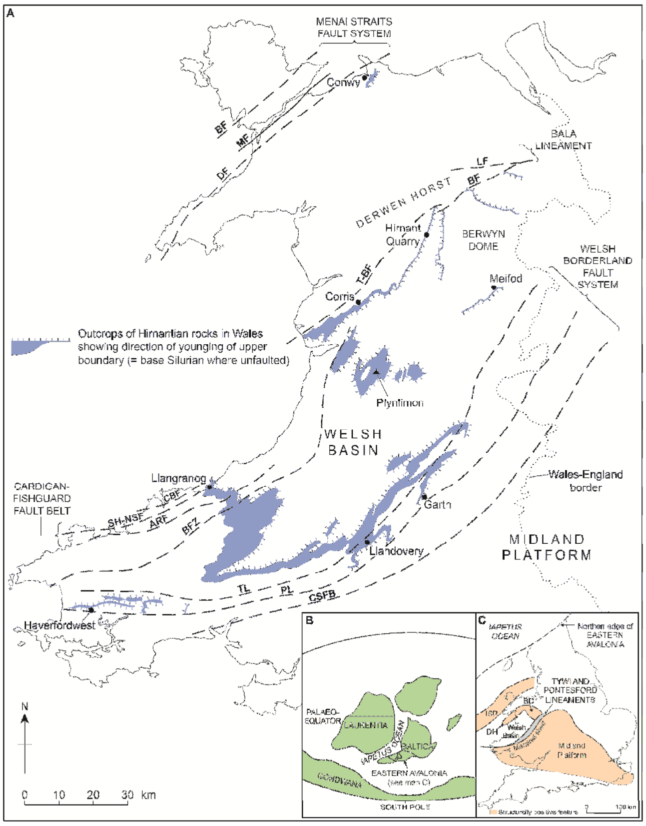

Figure 3.2 Hirnantian Outcrop in the Welsh Basin (figure from J.R. Davies et al. in preparation)

The relative quiescence of the tectonic activity allows the glacio-eustatic impact of the climate changes of the Hirnantian Stage to be seen in the rock record without the complication of the tectonic overprint associated with crustal uplift or basinal down-warping. This was coincident with a globally recognised "ice house" condition, with a glacial sedimentary record associated with the Southern Polar land mass (Gondwana). Glacio-eustatic sea level changes led to extensive emergence of basin margins (Davies, Waters et al. 2009(b)), shallowing of basin centres (Howells 2007; Schofield 2009; Fan, Peng and Melchin 2009), migration of the terrestrial / marine interface (Sheehan and Coorough 1990; Jones, Creel and Rios 2016) and erosion of the littoral and terrestrial realm (Brenchley, Marshall et al 2006).

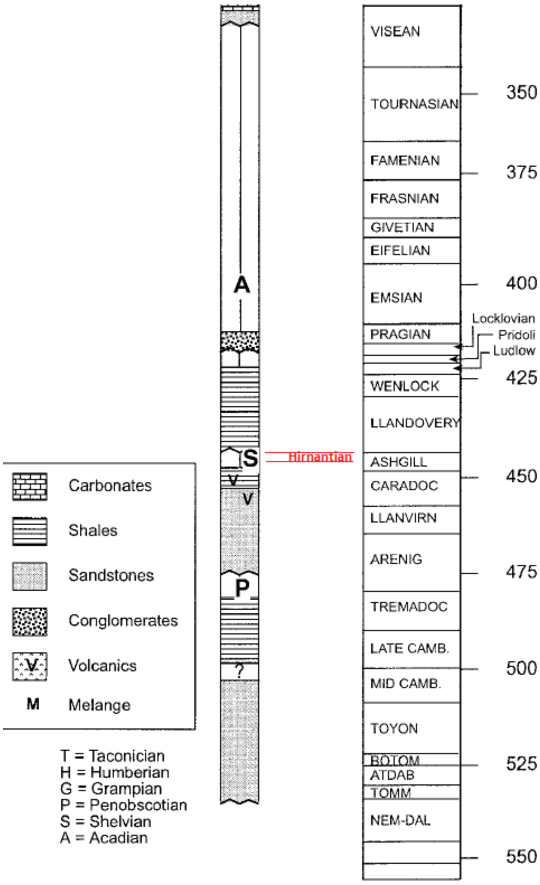

Figure 3.3 Placement of the Hirnantian tectonic regime – Post Penebscotian – pre-Acadian associated with Shelvian Phase (after McKerrow et al 2000)

Significant changes to the palaeo-ocean chemistry are also expected with pertubations of the carbon and oxygen cycles, changes in carbonate compensation depth, redox conditions etc. all potentially impacted by changes in the physical environment. It is to be anticipated that with such a period of environmental flux occurring, that this will impact significantly on the fauna of the day. Whilst there was little in the way of a complex terrestrial flora or fauna during the Hirnantian the marine ecology was well established. The faunal turnover associated with the Hirnantian Extinction Episode (HEE) is generally accepted to represent the second most significant extinction episode in the Phanerozoic record.

Associated with the post-*persculptus* faunal recovery transgressive sequences are apparent in the global rock record. The sedimentary architecture fits well with the concepts of sequence stratigraphy (Carter, Abbott et al. 1991) with the peak of the Hirnantian regression representing a Lowstand System Tract Boundary between regressive (Katian) and transgressive (post-*persculptus* Hirnantian and Rhuddanian) system tracts.

In a coastal and near shore environment it is anticipated that the effects of such major changes in the sedimentological regime will be evident in the rock record. It is relatively easy to construct a basic stratigraphical architecture to illustrate the anticipated facies relationships over time in this environment (Figure 3.4, below):

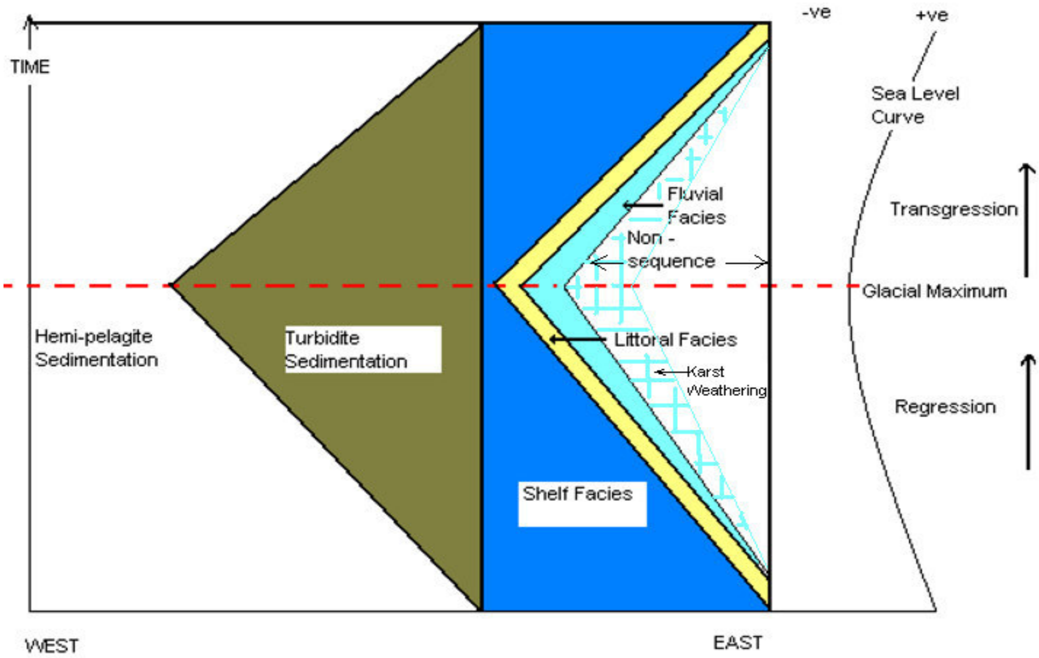

Figure 3.4: Sedimentological model for the Hirnantian sedimentary architecture of the Welsh Basin (modified from Nicholls, 2011).

This model postulates the presence of a significant hiatus in sedimentation (i.e. an unconformity) in the east of the model basin (associated with the influence of a land mass), a littoral and coastal facies that encroaches into the shelf succession during the regressive systems tract, (maximum encroachment during the glacial lowstand) and loss of associated shelf accommodation space, and a similar invasion of turbidite facies (or other mass transport mechanisms) from shelf to basin, with a reduction in the deep water laminated hemi-pelagite and pelagic sediments that constitute the "background" sedimentation in the deep-water basin environment.

The Hirnantian fauna (i.e. both the accepted constituents of the *Hirnantia* Fauna, and its less well recognised coexisting partners) lived within this changing environment, and by necessity would reflect the local environment, including all the “sticks and stones” associated with changes in weathering, climate, oceanography etc. The sedimentary record also reflects all these changes, and since the trace fossil record is a combination of the influence of both the faunal activity and the sedimentary processes the trace fossil record is a reflection, albeit incomplete, of the overall changes in the palaeoenvironment.

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Chapter 4

The Llangrannog Succession

*"There's a feeling I get – when I look to the west
And my spirit is crying for leaving"*

Jimmy Page and Robert Plant, 1971

"Aspicit et inspicit"
Giambattista Della Porta, 1589

The Llangrannog Succession

4.1 Geoconservation status

The coastline between Llangrannog Beach (SN 310 542) and Traeth yr Ynys Lochtyn (SN 317 550) is a designated RIGS (Regionally Important Geological / Geomorphological Sites) site with the following formal citation:

"*This coastal section is a regionally important site for several reasons. The Lower Palaeozoic sedimentary rocks exposed here, namely the Llangranog Formation and overlying Gaerglwyd Formation, span the late Ordovician - early Silurian boundary, a major time break in the stratigraphic column. Excellent exposure provides opportunities to obtain detailed information about these formations that can be used when following them and the Ordovician-Silurian boundary inland where exposure is generally poor. The Traeth Bach Member, the upper part of the Llangranog Formation, shows spectacular examples of folds and faults produced by slumping and other gravity-driven movements of the sediment before lithification. Dark mudstones in the sequence commonly contain well preserved graptolites that may be used to date the rocks. In parts of the Gaerglwyd Formation there are particularly clear examples of septarian concretions, unusual pillow-sized carbonate-rich bodies produced by chemical processes during lithification of the sediment. The rugged cliff line is a major scenic attraction of the Cardigan Bay coast, as recognized by the National Trust which owns parts of the RIGS.*"

In addition, the coastline is protected under a SSSI designation relating to the Aberarth – Carreg Wylan SSSI. However, the geological designation for this SSSI relates to Quaternary sections at Mwnt and Poppit (to the south of the study area) and to Caledonian structural features (Traeth Penbryn immediately south of the study area; and Mwnt), that is to say the significance of the remarkable soft sediment deformation and accompanying trace fossils are not recognised.

4.2 Lithostratigraphy

The study area comprises a 4km long coastal strip with extensive coastal outcrop. Inland outcrop is limited, but nevertheless road cuttings in particular, and occasional cut slopes associated with residential properties are apparent. The BGS mapping, and available published data suggest that the Katian *anceps* zone Nantmel Mudstone Formation (NMF) is present at the south of the study area, with the Hirnantian outcrop commencing at the northern end of Traeth Penbryn. Northwards we pass through the Hirnantian "Yr Allt" Formation and the overlying Cwmere Formation (*persculptus* zone), and the Silurian Allt Goch Formation is encountered at Traeth Pendinas Lochtyn at the northern end of the study area. There is therefore a generalised apparent dip towards the north exposed along the coast, with the oldest beds in the south, and the youngest in the north see Figure 4.1 below).

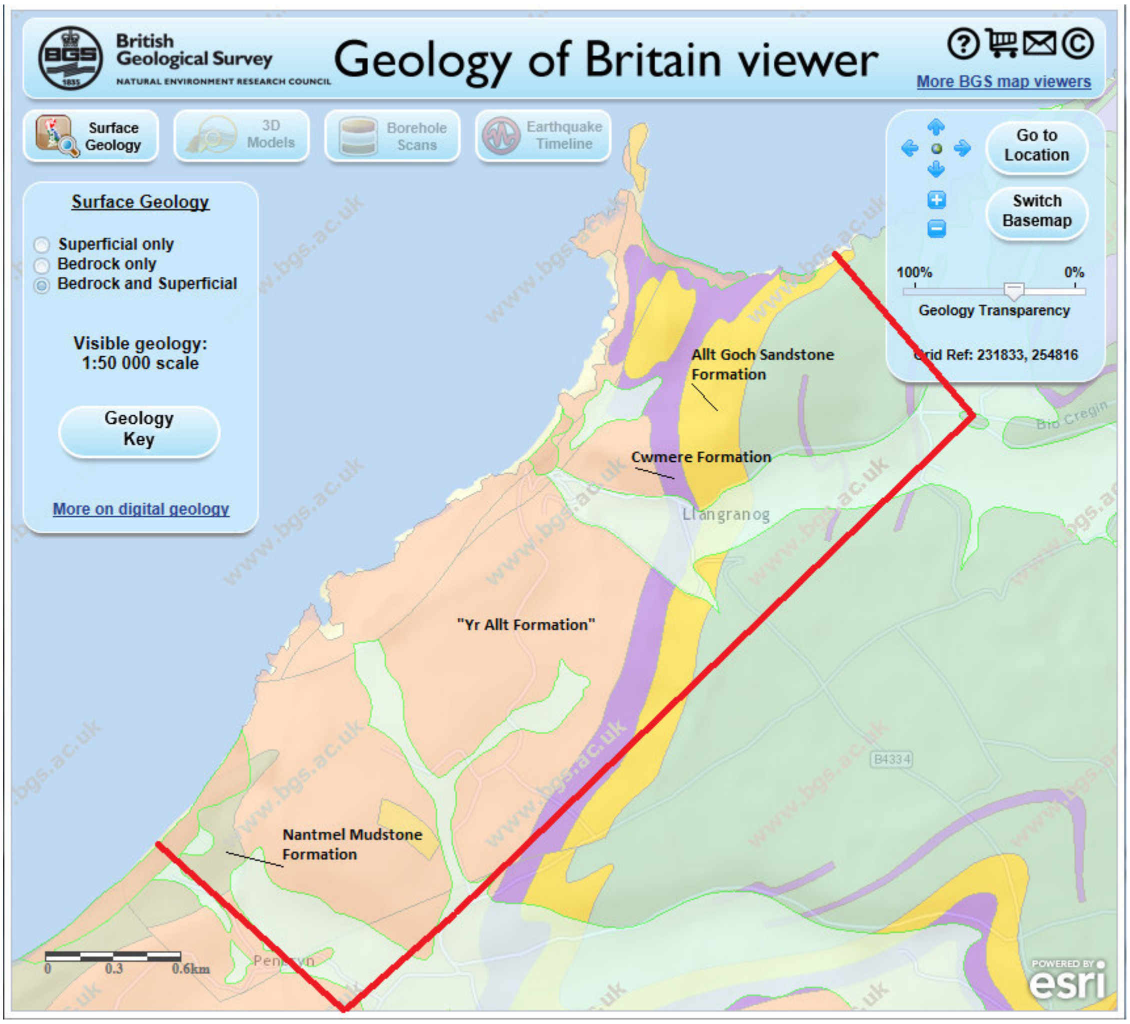


Figure 4.1: Current 1:50,000 Scale Mapping of Llangrannog and the surrounding area as shown on the BGS Geology Viewer Web site (study area shown in red). Reproduced under Open Government Licence: Contains British Geological Survey materials © NERC 2014

The history of early research in this area is, given the spectacular exposure available, surprisingly sparse. There have been however a number of stratigraphic schemes established and Table 1.2, (presented earlier) shows a comparison between these.

Lind-Hendricks (1926) described the stratigraphy of the "Bala" rocks in the district and described the following sequence of strata:

Orange weathering shales
Pyritous Mudstone
Ribbony Beds
Massive grits-thin grits-gritty mudstones
Gnarled Grits
Truncatus Beds

Research undertaken at the University of Dublin described by Ankatell (Ankatell 1987) reworked this stratigraphy substantially, merging Lind-Hendriks "Orange weathering shales" and "*Pyritous Mudstone*" into the "*Gaerglwydd Formation*" and merging the lower divisions into the "*Llangranog Formation*". The Llangranog Formation was further sub-divided into five Members.

A revised generalised summary of the regional stratigraphy was given in the re-publication of the Ordovician System standard correlation review (Fortey, Woodcock et al. 2000), although this followed the Ankatell scheme.

The British Geological Survey published a brief explanation (Davies, Sheppard et al. 2006) relating to Sheet 194 ("Llangranog") in 2006. This established the "*Cwmere Formation"* as the equivalent of the "*Gaerglwydd Formation",* and introduced the "*Yr Allt Formation"* to replace the upper portion of the *Llangranog Formation*, and the *Nantmel Mudstone"* to replace the lower portion.

(Davies, Waters et al. 2009 (b)) revised the nomenclature relating to the "Yr Allt Formation" of the district – and reassigned the rocks of the study area as being representative of the Drosgol and Brynglas Formations, established in the Aberystwyth District (Cave and Hains 1986). Research undertaken on the rocks immediately underlying the rocks at outcrop in Llangrannog was described Challands et al (2009).

During this study it has been apparent that there is little field evidence for the distinction / division made by Davies, Waters et al. (2009) in following Cave and Hains (1986); that is to say I have been unable to define an overlying slumped and less silty Brynglas Formation, in comparison to a sandier Drosgol Formation. There is a potential distinction in the field however, and that relates to the presence of so called "debrites", which are massively bedded units that retain little in the way of primary sedimentary textures. These are frequently associated with fluid escape structures, and are seen in places to be intrusive into overlying sediments. The distinction between the Drosgol and Brynglas Formation is deemed to be represented by the presence of such extensive debrite horizons. The "debritisation" event is associated with slumping of the overlying sediments. I take it therefore that the sandier units have been prone to liquefaction, and the boundary between the Drosgol and Brynglas Formations is a zone of profound disturbance, with the Drosgol Formation being the source of major instability, and the overlying Brynglas Formation being a mixture of autochthonous and allochthonous material. No *in situ* (undisturbed) boundary between the Brynglas and Drosgol Formations has been identified. As stated above however there are locations where the underlying Drosgol Formation is demonstrably intrusive into the overlying Brynglas Formation. Further detail relating to the extent of this wet sediment deformation (WSD) is described in Section 4.3 below.

A further distinction is apparent in that the vast majority of the trace fossils described in Chapter 5 occur as epichnial traces (Tier 0 or Tier 1 shallow burrows) on or just below bedding surfaces within the supposed Brynglas Formation. At the present time it is unclear whether this reflects a primary feature, i.e. the traces were never present (due to either the absence of trace makers, or the taphonomic conditions to allow preservation) or if they have been destroyed during the instability. For the moment, however, the presence of shallow epichnial burrows is taken to be diagnostic of the Brynglas Formation. Figure 4.2 (below) summaries the lithostratigraphy that is followed in this thesis.

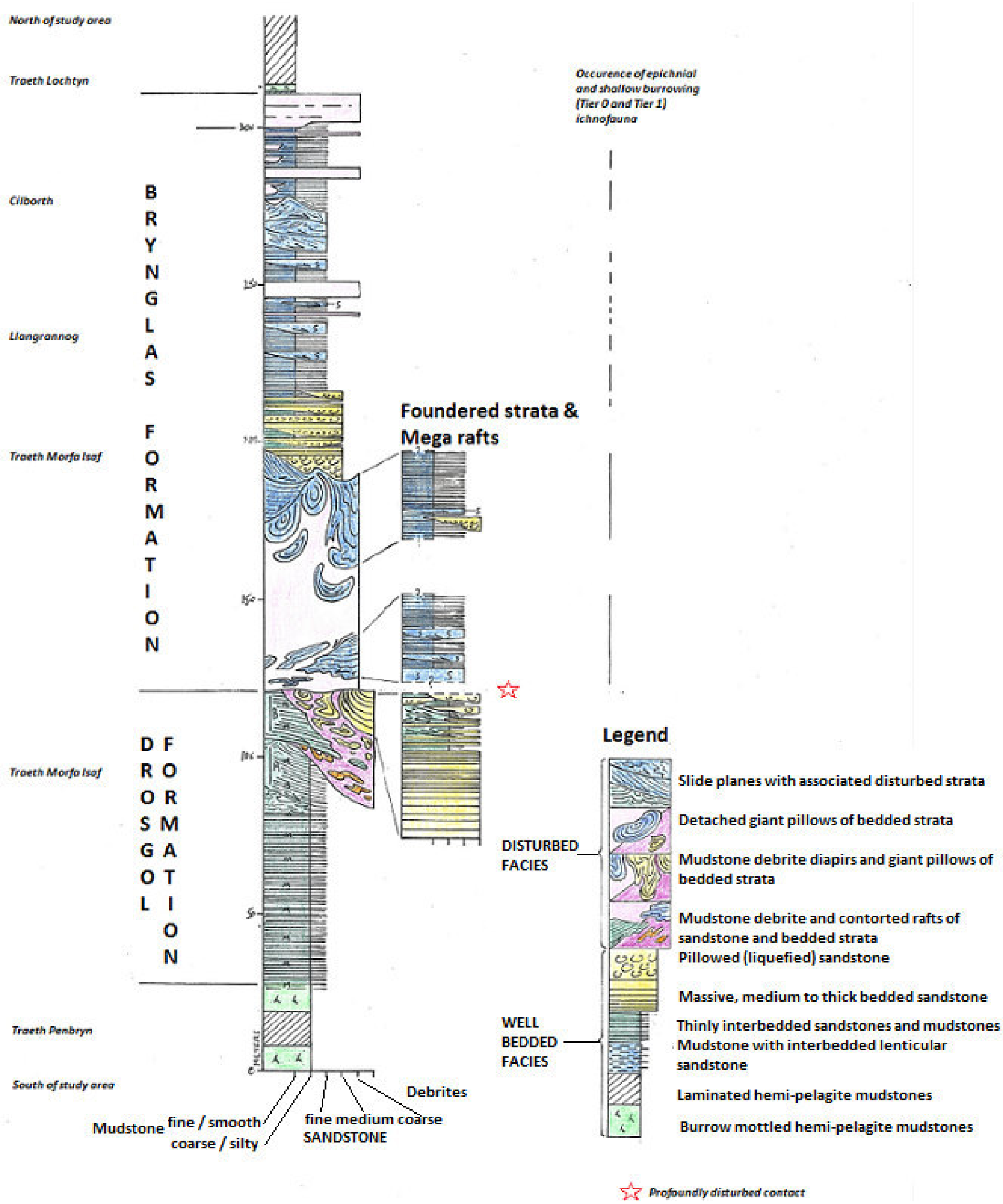


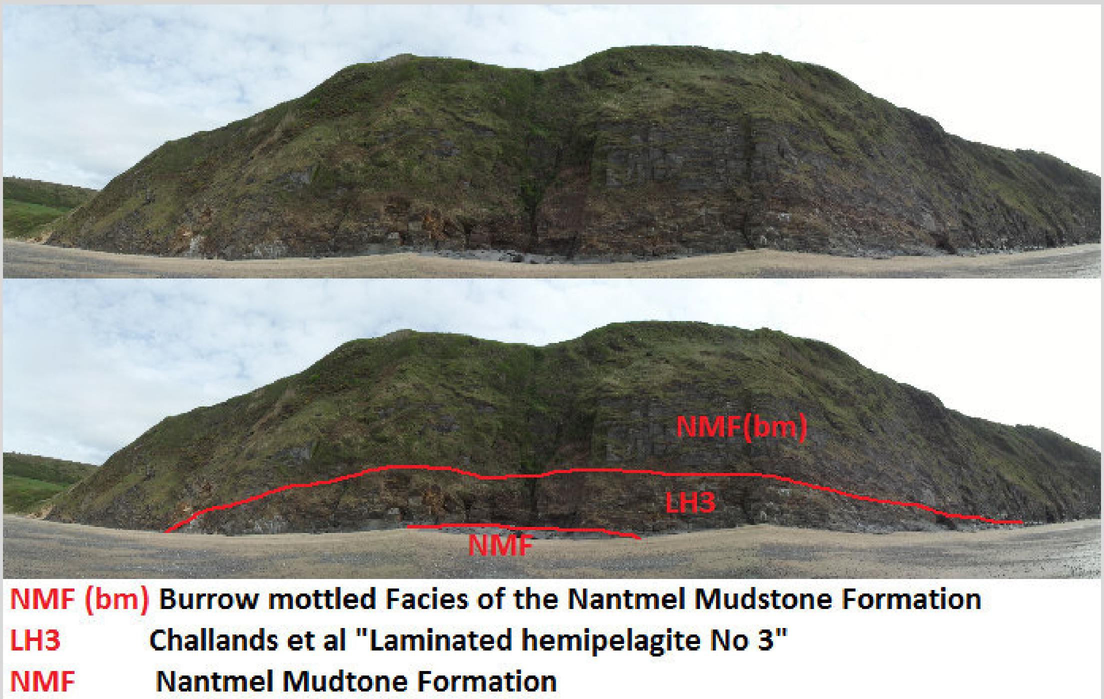
Figure 4.2 Detailed Lithostratigraphy – Llangrannog study area

4.3 Wet Sediment Deformation (WSD)

A brief description of the rocks exposed immediately to the south of the site at Traeth Penbryn is given in the greyed-out box on the following page. Within the study area itself the topmost beds of Challands et al. (2009) third laminated hemipelagite (LH_3) are seen at the most easterly point of the cliffs at the north end of Traeth Penbryn. These are overlain by the diagnostic burrow mottled facies of the Nantmel Mudstone Formation (NMF) (Figure 4.1 below).

Inset Box 2: Traeth Penbryn South (NGR SN290522)

This site is located immediately south of the study area in cliffs exposed at Traeth Penbryn. The contact with the overlying Hirnantian strata is seen within the study area at SN 294 527. A laminated hemipelagite lying between soft sediment deformed mudstone / siltstone couplets and the overlying burrow mottled facies is the LH3 unit of Challands et al (Challands, Armstrong et al. 2009). The site also lies within a SSSI although the geological designation relates to Caledonian structures (Traeth Penbryn and Cwmtudu) and Quaternary geomorphological features (Mwnt and Poppit) (Anon, 2002).



The "burrow mottling" is a consequence of the presence of the ichnogenus *Chondrites* von Sternberg (1833). Challands (2008) indicates these rocks to be of *anceps* zone age, and broadly coeval with the "Red Vein" strata elsewhere in the Welsh Basin. Cliffs are approximately 30m high.

The NMF is in turn overlain by the well bedded sandstone and siltstone strata of the Brynglas Formation with an intervening "debrite" dominated horizon of the Drosgol Formation. The basal Drosgol Formation is represented by an 'initial facies' of distal turbidite couplets, before giving way to massively bedded, and profoundly disturbed debrite bearing strata. These debrites occur throughout the succession, but in the Brynglas Formation are typically bed scale units of disturbed siltstone. Within the Drosgol Formation these debrites locally form thick and laterally extensive basal sliding planes for mass movements of the overlying pre-lithification Brynglas Formation. As well as occurring as near conformable planes these debrites also occur in high angle disconformable aspects, which have been ascribed to diapirism (Davies, Sheppard et al. 2006). The exact mode of formation of these debrites remains a matter of debate, and the extent to which they represent lithified sediment "flows" is unclear, although the presence of such "debrite" horizons within the Drosgol Formation (previously unsub-divided "Yr Allt Formation" have been described by others (Davies, Sheppard, Waters and Wilson 2006) as follows:

"Also common in the Yr Allt Formation are thick, parallel-sided, debrite beds, comprising massive silty mudstone with 'balls' of sandstone and bedded rafts of the undisturbed silt-laminated mudstone. Such beds range in thickness from less than a metre, within sequences of disturbed strata, up to several metres, possibly as amalgamated units."

Observations made during this study suggest that the debrite horizons within the Drosgol Formation actually represent a series of basal failure planes of varying scales, associated with a major shelf collapse that occurred post- Brynglas Formation deposition, but prior to the sedimentation of the Cwmere Formation, affecting tens of metres of soft sediment in the Drosgol and Brynglas Formations. These events were associated with extensive forced dewatering of the sediment.

The debrite beds generally appear massive and retain only an irregular bedding which is locally discordant to the bedded horizons either side of the debrite. However, the debrites are also seen locally to retain an older, highly folded and much finer lamination / close bedding. The massive appearance is therefore thought to be a result of hydraulically mediated destructuring rather than being a primary sedimentary feature.

At Carreg y Nodwydd (Figure 4.3, also shown as Plate 1 in Davies et al 2006) the Brynglas Formation appears to be an intact sedimentary allochthon. The underlying Drosgol Formation has failed hydraulically, with the interbedded sandstone horizon having "blown". At this location the overlying bedded units have retained their integrity, and any internal deformation of the allochthon has been minimal.

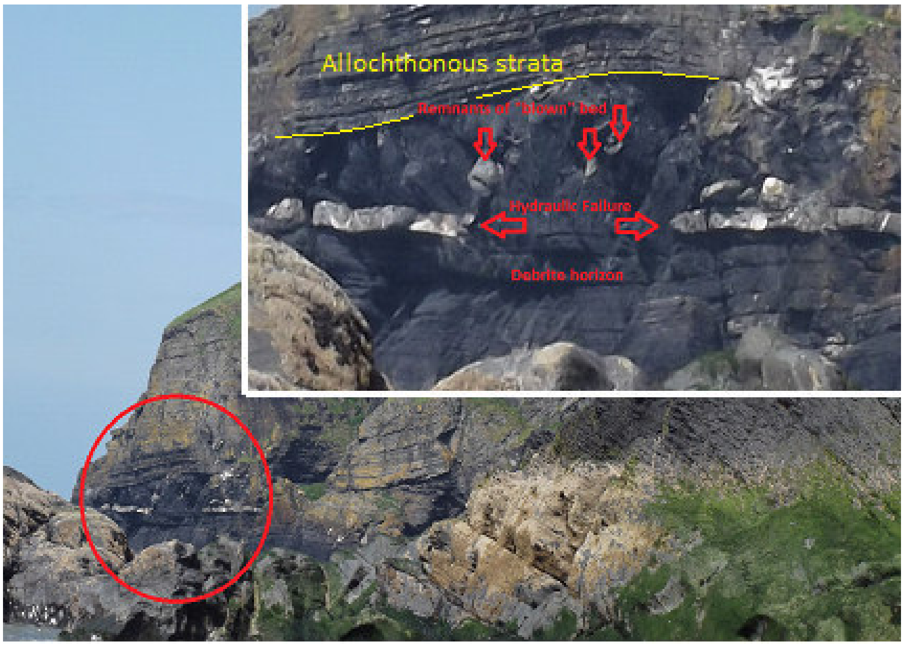


Figure 4.3: Carreg y Nodwydd (SN297533) Showing the "profoundly disturbed" contact between bedded strata and overlying disturbed facies. The inset shows a close up of a hydraulic failure below allochtonous bedded strata in upper most Drosgol Formation

Immediately north of this headland is the beach known as Traeth Morfa Isaf or Traeth Bach. At the rear of the beach the debrite horizon acting as a sedimentary "injectite". It takes the form of a discordant intrusive body, reminiscent of a basalt dyke (see Figure 4.4).

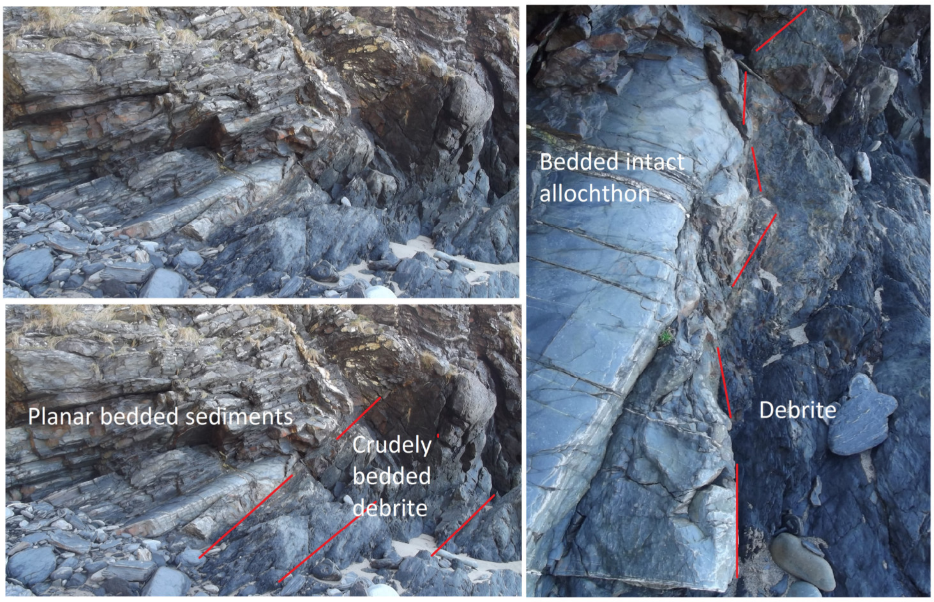


Figure 4.4: Traeth Bach (SN299535) Crudely bedded debrite horizon acting as a diapiric intrusive "Dyke" within bedded sequence.

In the northern cliff face of the Traeth Bach embayment, described by Challands in his PhD thesis (Challands 2008). Figure 4.5 shows the relationship between the debrite horizon (the top shown in blue) and the overlying highly deformed allochthon (bedding picked out in red), and also shows evidence of a significant forced dewatering structure, with what appears to be a sand volcano pipe, and ejecta debris cone (yellow). As can be seen, this is different from the interpretation put forward by Challands who described this feature as a fault.

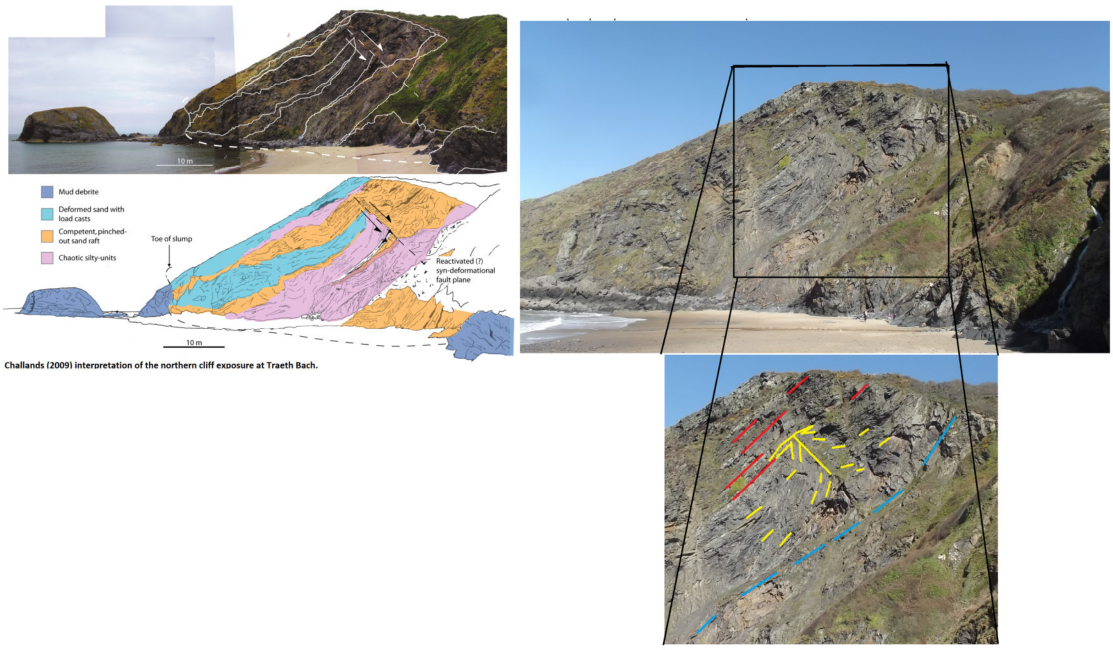


Figure 4.5: Traeth Bach Northern Cliff Face (SN301535) The red colouration indicates overlying flat-bedded sediment, the blue intact underlying bedded sediment. The intervening (yellow) strata are disrupted.

At the southern side of the beach (Figure 4.6) the debrite material (Drosgol Formation) is seen to be intruded along the base of soft sediment “thrust” structures with the overlying allochthonous “hanging wall” strata presenting as a series of discordant “ramps”, and concordant “flats”, using the terminology developed for thrust tectonics (Boyer and Elliott 1982).

At the southern cliff face of the main beach at Llangrannog village. There is significant structural complication associated with a Caledonian synclinal fold. Nevertheless, the majority of the deformation seen in the exposed cliff faces is thought to represent a large-scale soft sediment “pop-up” structure of the Bryngas Formation above debrites in the Drosgol Formation.

Figure 4.6 Trwyn Traeth Bach (southern headland at Traeth Morfa Isaf - SN 299 535) Drosgol Formation debrites acting as sedimentary injectites into overlying Brynglas Formation strata. Field of view approximately 15m.

In the northern cliff face of the main beach at Llangrannog we see again the effects of Caledonian folding in the form of a synclinal structure, most evident by the westward dipping bedding at the rear of the beach (immediately alongside the beach café). Much of the structural complication seen in the cliffs is however of soft sedimentary origin.

Figure 4.7: Llangrannog Northern Headland. This image shows the impact of substantial soft sediment folding caused by displacement associated with a debrite horizon that immediately underlies this outcrop. The same Caledonian synclinal fold brings the debrite to exposure immediately east of this outcrop, as shown in Figure 4.8 below. Rucksack in foreground for scale is approximately 0.75m high, overall field of view is approximately 15m.

Figure 4.8: Debrite horizon decollement below the intensely folded exposure shown in Figure 4.7 brought to surface by Caledonian folding. The soft sediment folding is picked out in yellow. The sheared zone has been steepened by Caledonian folding and would have been only gently dipping at the time of the soft sediment instability. Rucksack in foreground for scale is 0.75m high, cliffs are approximately 15m from sand to vegetation.

This location adjacent to Carreg Ifan (Figures 4.9 and 4.10) is only accessible at low tide on spring tides, and is located beneath steep actively eroding cliffs. The debrite horizons are horizontally bedded and make up much of the lower part of the cliff slopes. At this location there is relatively little soft sediment folding in the overlying sediments, with the deformation apparently occurring as a result of soft sediment sliding on discrete decollement horizons with the overlying sediment retaining its integrity.

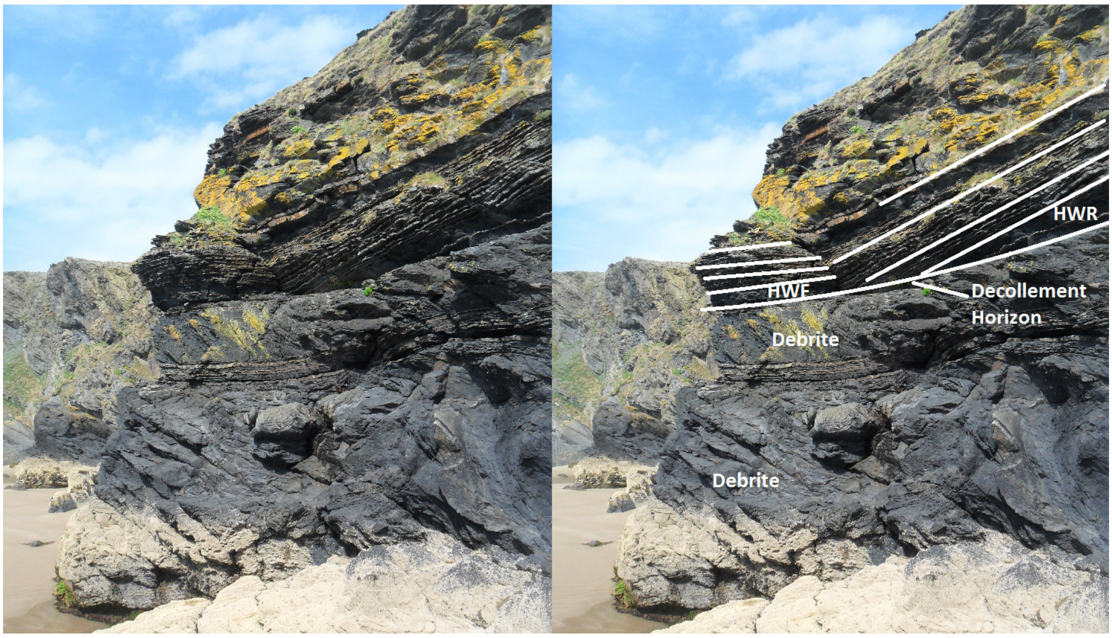


Figure 4.9: Carreg Ifan. At this location the debrite horizon is near horizontally bedded, as are remnant intact stringers of sandstone. However, above the debrite (top right of picture) the bedded sandstone stringers are locally discordant. At the far end of the outcrop they are concordant, indicating a change from a hanging wall ramp (HWR) to a hanging wall flat (HWF) above the decollement horizon. Cliff section in view is approximately 5m high

Figure 4.10: Carreg Ifan, Location as Figure 4.9. The debrite horizon is here seen to include a number of disturbed blocks and rafts which are believed to have "blown"

as a consequence of the hydraulic failure of the debrite sediment horizon. The position of the footwall flat associated with the local decollement can be seen as a preferentially eroded notch at the top of the image. The image represents approximately 6m by 4m field of view.

Figure 4.11 (below) is from the southern flank of the Ynys Lochtyn headland. The feature is a remnant shaft of a sand volcano feature formed during forced dewatering of the overlying soft sediment during hydraulic failure. This is in essence an "effective stress" response to loading imposed during liquefaction and landslide emplacement, with local increased pore water pressure being vented through this conduit.

Figure 4.11: Sand volcano shaft (dewatering structure) in debrite horizon. Ynys Lochtyn, Llangrannog. Top and bottom are different aspects of the structure. Scale rule on lower image is 150mm long.

On the northern flank of Ynys Lochtyn is one of the few locations (Figure 4.12) where almost complete destructuring of the debrite has not occurred and some vestigial sedimentary structure remains showing the extent to which plastic flow of the material has occurred resulting in folding of the debrite material.

Figure 4.12: North side of Ynys Lochtyn Headland. As with the southern side of the headland the upper surface of the debrite horizon is forming a local wave cut platform. At this location however, the fabric of the rock has not been wholly destructured and intense local folding is apparent. The overlying sedimentary deposits are sub-horizontally bedded.

In summary it has been shown that the rocks around Llangrannog record both local (individual bed scale) instability which started in *anceps* zone strata, before developing into a complex large scale (involving tens of metres of sediment) slope failure which appears to predate the *persculptus* biozone sedimentary deposits. Figure 4.13 shows an illustration of the shelf instability mechanisms apparent.

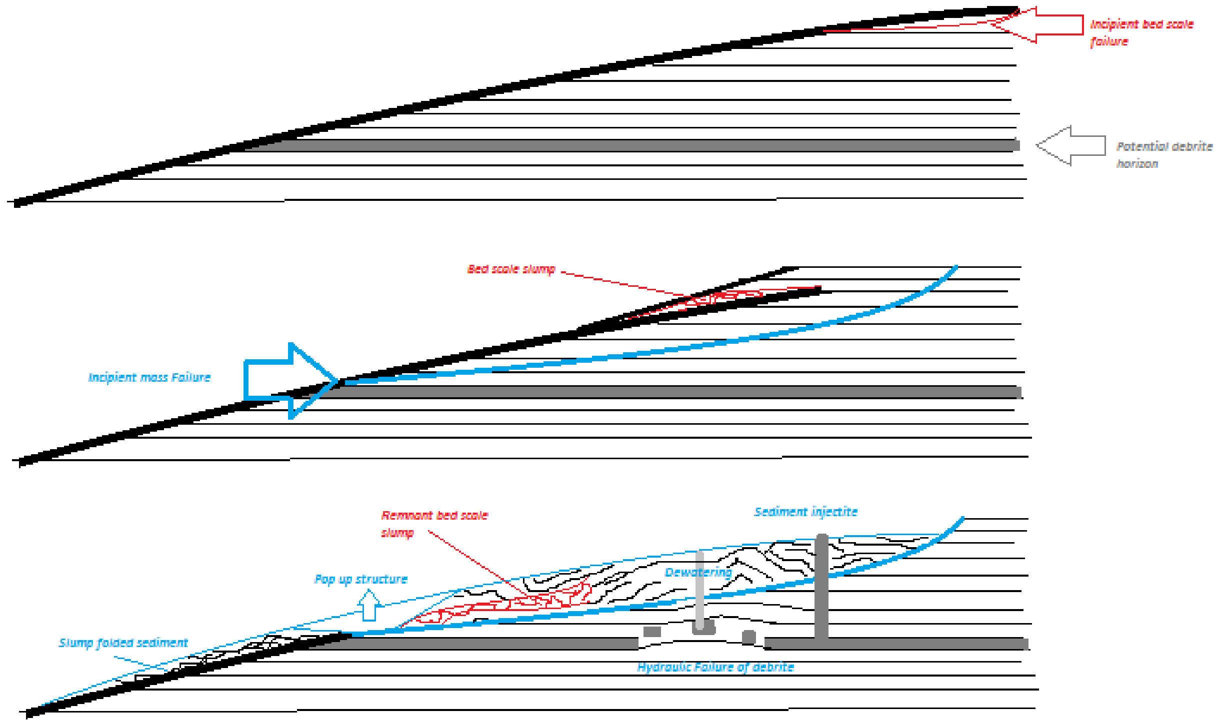


Figure 4.13: Cartoon style illustration of the various scales of soft sediment instability associated with Hirnantian sedimentary deposits in the Llangrannog area.

It should be noted that near the top of the Drosgol Formation there appear to be multiple potential initial starter horizons from which the shelf instability can originate. This progression of sedimentary processes can be summarised as shown in the summary sedimentary log as presented in Figure 4.2).

It is apparent that in the Drosgol Formation, above the burrow mottled facies of the NMF no ichnofauna are recorded. However, above the horizon of profound disturbance which lies between the Drosgol and Brynglas Formations shallow burrowing, and in particular epichnial surface trace fossils are widespread. In the following chapter the ichnocoenose of the Llangrannog area is described in detail.

4.4 Structural Geology

Structural analysis of what has been called the "Llangranog Lineament" was described by Craig (Craig 1987). This feature is one of a series of north easterly to south westerly trending faults in the area (the Bronant Fault- Mynydd Bach Fault, the Claerwen Fault and the Cwmysgawen Fault) which follow the regional strike, and movement on them has significantly impacted on the developing basin sedimentation through the Ashgill and continuing into the Llandovery and Wenlock (Davies, Ray et al 2011).

Reference to the previous Figure 4.1 shows the relatively simple structure that the outcrop pattern of the Cwmere Formation and the overlying Allt Goch Formation make as they strike slightly east of north approaching the coast. However, the apparent outlier of Allt Goch Formation at Pendinas Lochtyn does not follow the same simple structural style. On approach to the Llangranog Lineament the strata are seen to be folded into a relatively tight northward plunging syncline (Figure 4.14).

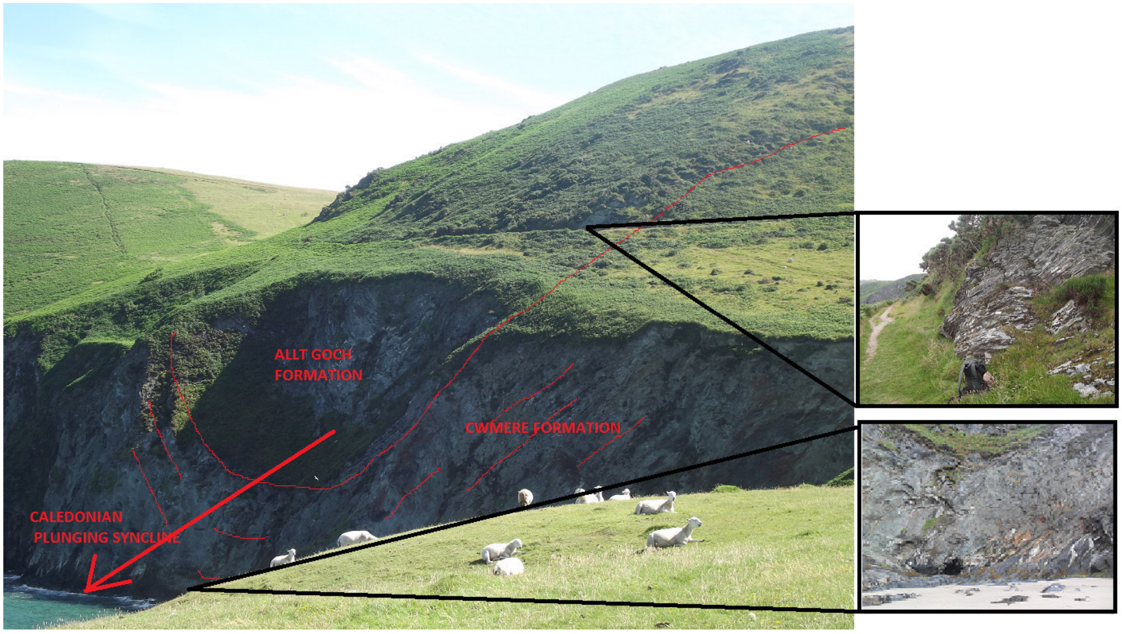


Figure 4.14 Plunging syncline at Traeth Pendinas Lochtyn. Insets show northerly plunging bedded strata visible on coastal footpath and the synclinal axis exposed at beach level (accessible at low tide).

This fold structure lies tight up against a fault which separates the mainland from the peninsula of Ynys Lochtyn. Field relationships show the presence of Drosgol Formation debrites beneath trace fossil bearing Brynglas Formation to the west of the fault, lying against Mottled Mudstone Member and Cwmere Formation strata to the east. This implies that the downthrow on the fault is to the east, and therefore the Llangranog Lineament would appear to be of opposite sense to the Bronant / Claerwen and Cwmysgawen Faults further east. This implies the presence of a graben type structure.

Similar Caledonian style open folding is apparent at the northern end of Traeth Penbryn (Fig 4.15), at Cilborth Beach (Figure 4.16), and at Llangrannog Southern Cliff Face (Figure 4.17).

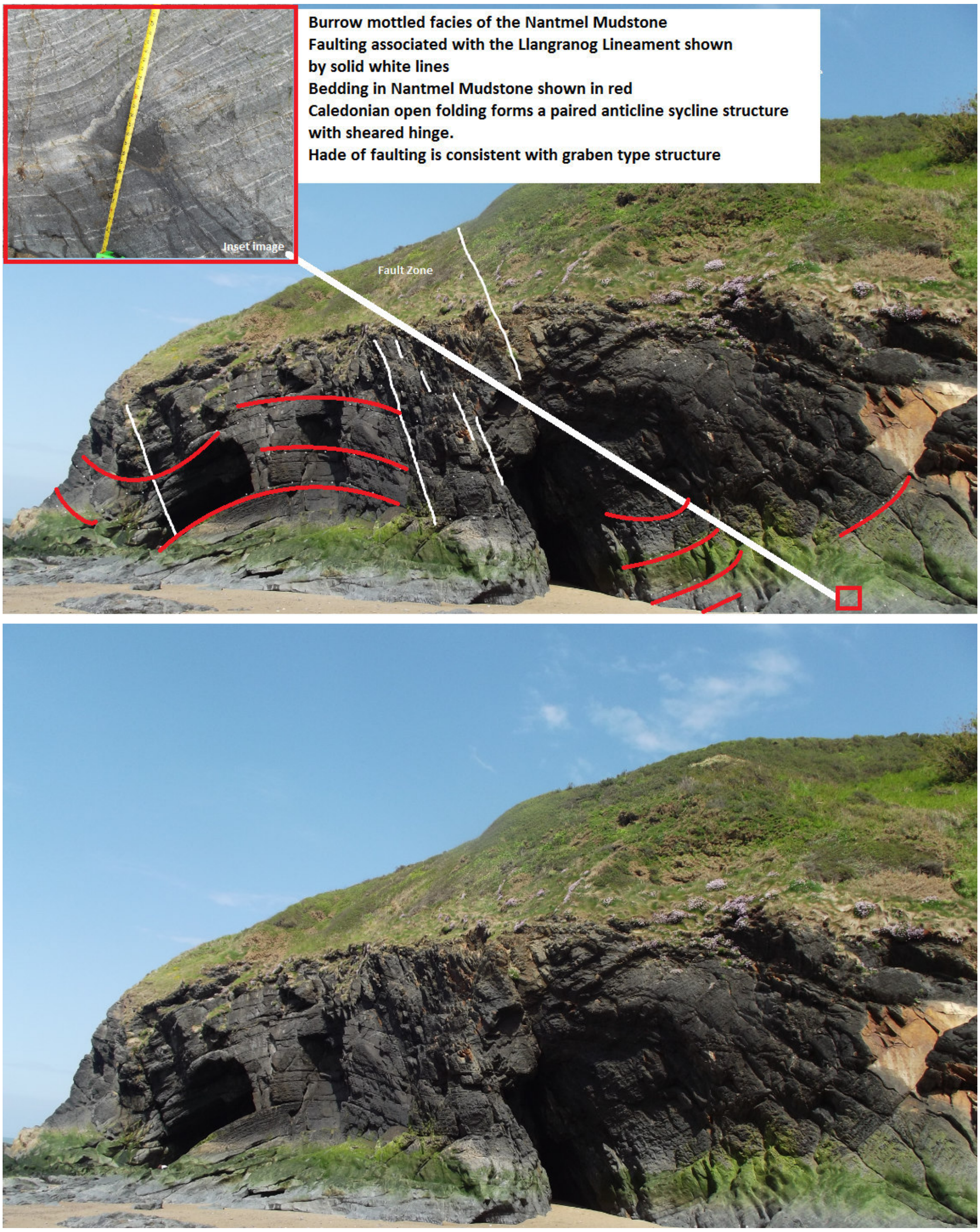


Figure 4.15: Traeth Penbryn North (SN 293 526), the oldest rocks in the study area (note Caledonian open style folding). These rocks are the well bedded facies of the Drosgol Formation.

Figure 4.16: Northerly plunging open Caledonian syncline in Brynglas Formation at the northern end of Cilborth beach. The structural trends are overprinted on the WSD style deformation.

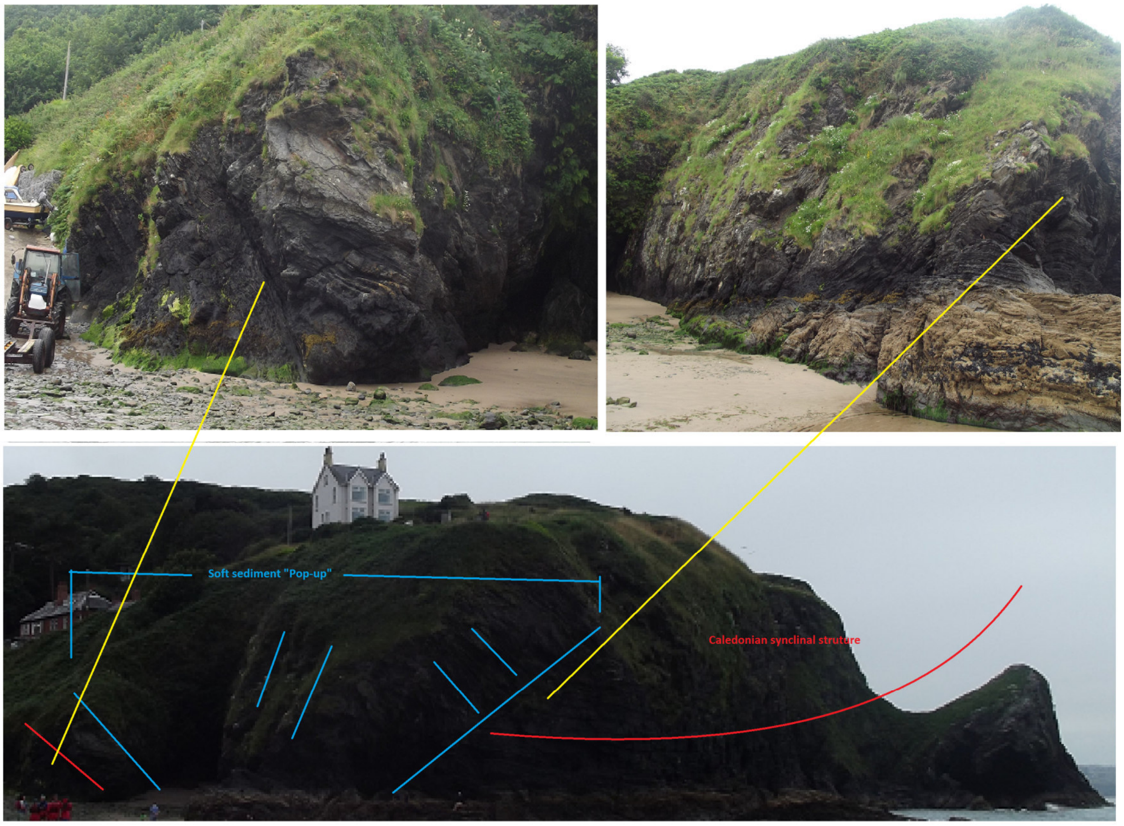


Figure 4.17: Llangrannog Southern Cliff Face showing soft sediment "pop-up" structure (blue lines indicate major sedimentary bedding planes and decollement horizons) older than the Caledonian structural elements (a syncline) represented by the red lines. The footwall below the pop up to the west (right of the image) is near horizontally bedded therefore the angle of the frontal soft sediment "thrust" is close to the original aspect. On the contrary, the footwall behind the eastern part (left of image) of the pop-up has been made to appear over-steep by the Caledonian folding.

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Chapter 5

Detailed taxonomy and ichnology of the Llangrannog Succession Trace Fossils

"And, departing, leave behind us
Footprints on the sands of time;"

Henry Wadsworth Longfellow. 1838

Detailed Description of the Llangrannog Succession Trace Fossils

5.0 Introduction

This Chapter gives detailed taxonomic descriptions of the trace fossils identified during the course of the field work. Ichnotaxonomic nomenclature follows the recommendations of the International Code for Zoological Nomenclature (ICZN 2012). Use of open nomenclature follows the recommendations of Bengston (1988) where appropriate. It should be noted that ichnospecific nomenclature is considered to be of dubious practical worth in many cases, and therefore no attempt is made to extend the nomenclature to the ichnospecies level without appropriate defining features within the ichnotaxabases present. If appropriate "variations" are identified these are noted as variations within the established ichnogenera without necessarily implying a different ichnospecies.

The majority of the material described has not been collected, as the act of excavation and removal of these trace fossils would be destructive. A small number of samples were suitable for collection, either as fallen loose blocks, or else readily removed by hand, and these are identified by the presence of Sample Reference Nos: shown thus: **KHN00XX**. No museum repository numbers are available at the current time whilst permanent curation is arranged.

Details of the locations of the figured specimens are given in Figure 5.37. All scale bars represent 1cm unless otherwise stated.

The concept of ichnofacies and in particular trace fossil bathymetry has been important in sedimentological and palaeoenvironmental studies since it was first introduced by Seilacher (1925-2014) in German in 1953, and in English in 1967 (Seilacher, 1953, 1967). The key principle established is that collections of trace fossils, or ichnocoenoses, are recognisable over long geological periods in similar palaeoenvironments. These allow definition of ichnofacies which relate to sedimentary facies in a predictable manner and have been discussed widely in relation to the Welsh Basin previously (Orr; Crimes and Crossley).

In the rocks around Llangrannog however we seem to encounter something of a paradox. Whilst the trace fossil *Nereites*, and the apparently related *Curvolithus* are typically associated with the deep shelf *Nereites* ichnofacies, other indications of bathymetry in the rocks are suggestive of shallow water conditions including extensive wave rippling and the apparent presence of Microbially Influenced Sedimentary Structures such as *Kinneyia*.

Despite then, the presence of the eponymous ichnogenus *Nereities* itself, as well as other nereitid ichnogenera such as *Curvolithus* this appears to something of an aberrant ichnocoenose. In addition to the shallow water sedimentary features apparent, there is also relatively frequent occurrence of *Diplichinites / Merastomichnites* ichnogenera which are much more typical of the shallow water *Cruziana* ichnofacies. The *Cruziana* ichnogenera itself has also been identified, albeit only at a single location.

The ichnofauna identified within the *extraordinarius* graptolite biozone (i.e. associated with the extinction episode) appear to be of nereitid affinity but to be of shallow water origin. This is presumably a reflection of the absence of the normal burrowing activity associated with benthic macrofauna, and reflects the extinction episode amongst the trilobites and echinoderms. The absence of the burrowing fauna leads to a loss of what Wright and Cherns (2016) call the Taphonomically Active Zone. This in turn is associated with a loss of Tiering in the observed trace fossil assemblage, and the assemblages become dominated by epibenthic and a shallow burrowing benthic fauna working at the mud-ground / firm-ground interface. This restructuring therefore makes traditional bathymetry based on ichnofacies redundant in stressed palaeoecologies.

In general terms the macro-fauna of the Hirnantian is impoverished and of restricted diversity. This is as a consequence of both biotic factors (low standing diversity) and taphonomy (poor preservation potential in regressive sequences). There is evidence from both the Hirnant Valley, and more so from Llangrannog, that there is a significant presence of microbially influenced sediments. These include a number of enigmatic bedding surfaces (see Specimens KHN0005 and KHN0016), and other structures such as *Kinneyia.* Specimen KHN0036 for example is a biofilm in the process of desiccation found in the Foel-y-Ddinas Formation, Cwm Hirnant. This is likely to be a consequence of the eastern position and probable local sub-aerial exposure – as implied by apparent karstic weathering of the immediately overlying Hirnant Limestone Member. By way of contrast the biofilms seen in the vicinity of Llangrannog (KHN0094 for example) show no destructive features and appear not to have suffered any immediate post-sedimentation sub-aerial exposure. However, the frequent appearance of ripples, associated with the microbial mats does imply that the Brynglas Formation reflects a shallow water environment, associated with the acme of the glacial lowstand.

The microbial mats are anticipated to have formed the basis of the extinction related food chain. This is supported by the dominance of trace fossils comprising either epibenthic surface burrows, or shallow burrows amongst the ichnofauna. This phenomena – the loss of the sedimentary “mixed layer” has also been recorded associated with the end Permian mass extinction episode (Hofmann, Buatois et al. 2015). In seemingly abandoning the deeper benthic ecological niches that were increasingly occupied from the Cambrian through the Ordovician (Droser and Bottjer 1989; Seilacher, Buatois et al. 2005) it appears that the direction of evolutionary “progress” is reversed, and the Hirnantian palaeoecology is seen to mimic in some ways the situation of the late Pre-Cambrian Ediacaran “Vendobiota”(Mapstone McIlroy 2006; McCall 2006) with soft body fauna at an evolutionary advantage.

The microbial mats form the basis of a food chain which involved agrichnial sub-mat mining by the maker of the *Gordia* and *Nereites* type ichnogenera, as well as surface grazing by the *Curvolithus* animal. It seems likely that the evidently motile creator of the *Diplichinites / Merastomichnites* traces was the apex predator of the Hirnantian Welsh Basin.

5.1 *CURVOLITHUS*

Ichnogenus: *CURVOLITHUS* (Fritsch 1908),

Ichnospecies: Variation Type i

Mode of preservation: Epichnial semi-relief
Occurrence:
Cilborth beach, Llangrannog SN311544, Brynglas Formation
Lochtyn Beach, Llangranog SN312545, Brynglas Formation

Description: Typically between 6mm and 12mm diameter, straight or gently curved trace. As described in Treatise Part W comprises smooth central stripe (6-10mm) with narrow lateral ridges (Hantzschel 1975). Ridges are locally seen to be striated at < 1mm separation. Locally ridges are seen to become subdivided into ovoid / almond shaped pellets.

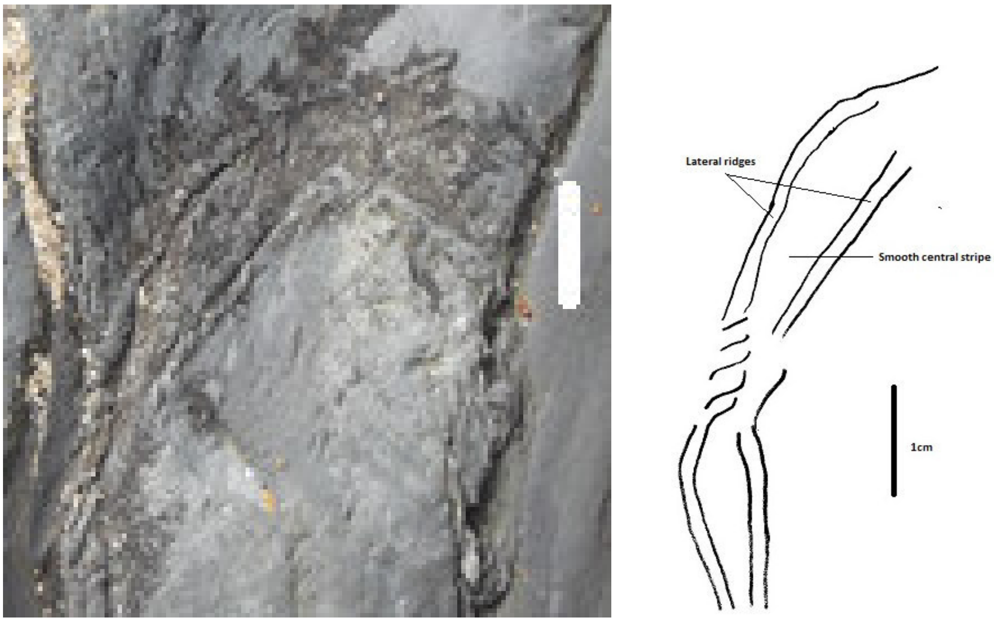


Figure 5.1 Curvolithus, Variation Type i : A single trace approximately 8mm wide on a bedding plane surface.

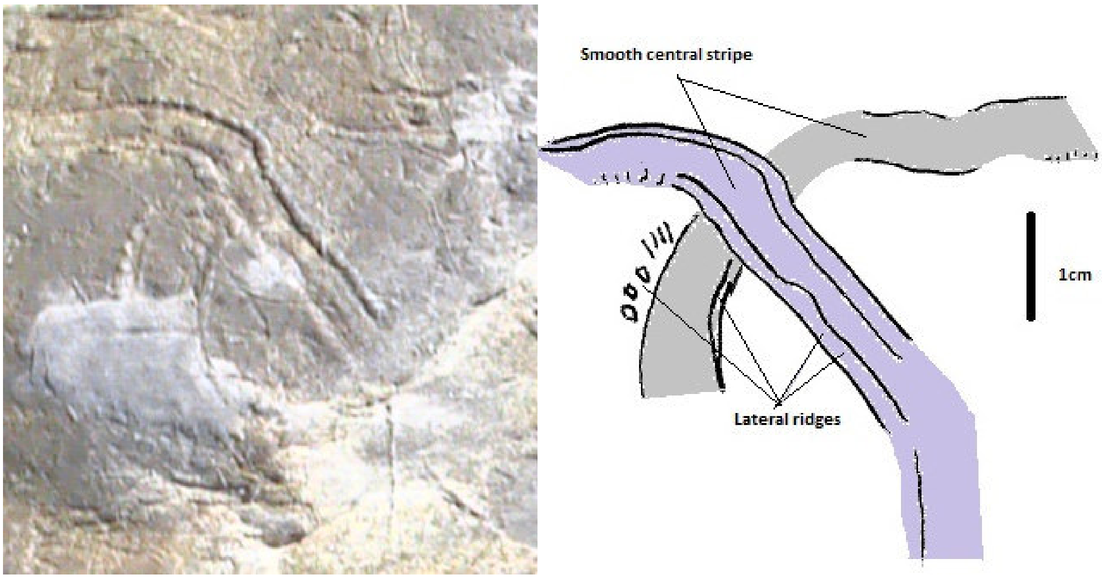


Figure 5.2 ***Curvolithus*****, Variation Type i, 2 No. traces showing crossing behaviour. Note crenulation apparent locally on lateral ridges.**

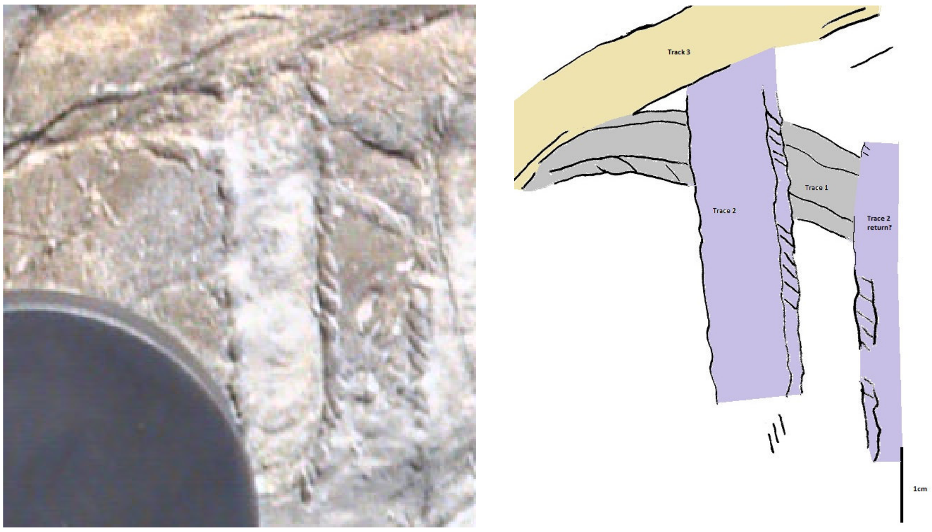


Figure 5.3 ***Curvolithus*****, Variation Type i, 3 No. traces** ***circa*** **10mm diameter showing crossing behaviour. Lens cap is 50mm diameter.**

Ichnogenus: *CURVOLITHUS* (Fritsch 1908),
cf *PALAEOBULLIA* (Gotzinger and Becker 1932)
Ichnospecies: Variation Type ii

Mode of preservation: Epichnial semi-relief
Occurrence: Cilborth beach (Northern cliff section), Llangranog SN312544,
Lochtyn Beach, Llangranog SN312545 Brynglas Formation

Description: As for *Curvolithus* Type 1 except meniscate markings in central area. The trace is gently curved and lateral ridges differ. On curved examples the ridge on the inside of the bend is sub-divided into chevronate imprint marks whereas on outside of bend ridge is formed from ovoid / almond shaped pellets, Figure 5.5 shows a single trace change from Type i to Type ii *Curvolithus* along the length of the trace, indicating their synonymy.

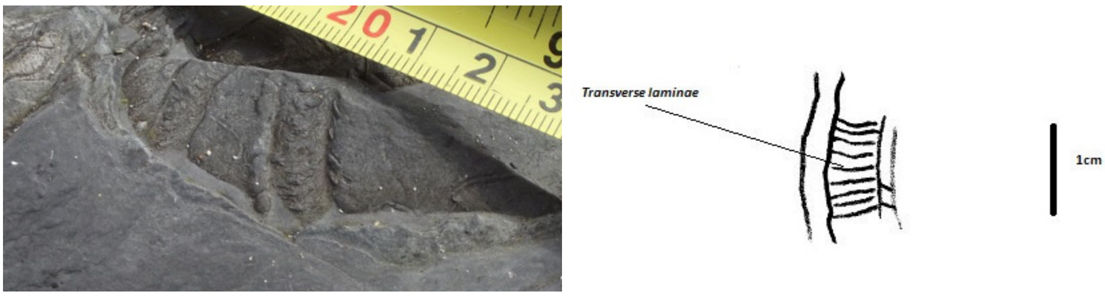


Figure 5.4 *Curvolithus*, Variation Type ii with distinct gently curved transversely orientated laminae. Cilborth Beach.

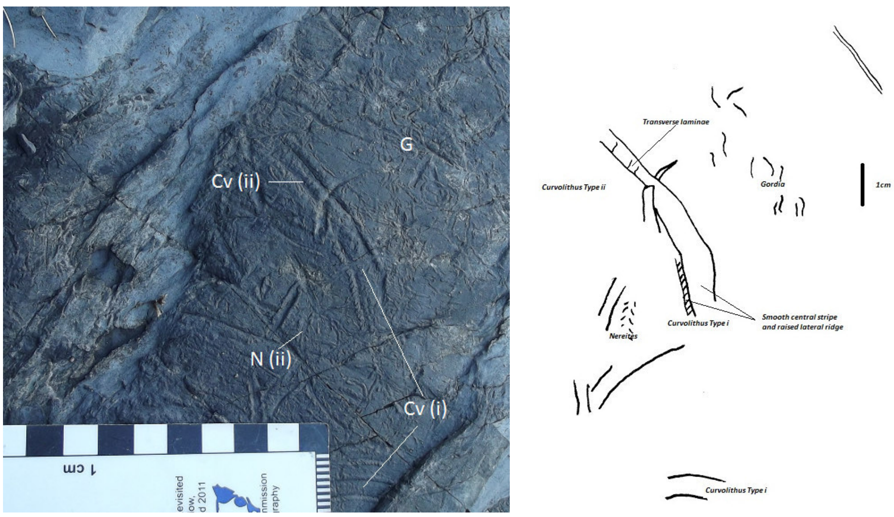


Figure 5.5 Occurrence at Lochtyn Beach (Brynglas Formation). Bedding plane showing extensive bioturbation including *Curvolithus* Type I (Cv (i)), *Curvolithus* Type ii (Cv (ii)), *Gordia* "scribbling traces" and poorly preserved *Nereites* Type ii.

Ichnogenus: *CURVOLITHUS* (Fritsch, 1908),
c.f. *PALAEOBULLIA* (Gotzinger & Becker, 1932)

Ichnospecies: Variation Type iii

Mode of preservation: Epichnial semi-relief
Occurrence: Cilborth beach (Northern cliff section), Llangranog SN312544, Brynglas Formation

Description: 3-4mm wide trace consisting of a slightly raised central line, flanked by pair of smooth open "U" channels, with chevronate flanking ejectementa ridges. Faint transversely striated markings at regular spacing (c 4mm) along the trace may represent peristaltic compression of the trace maker.

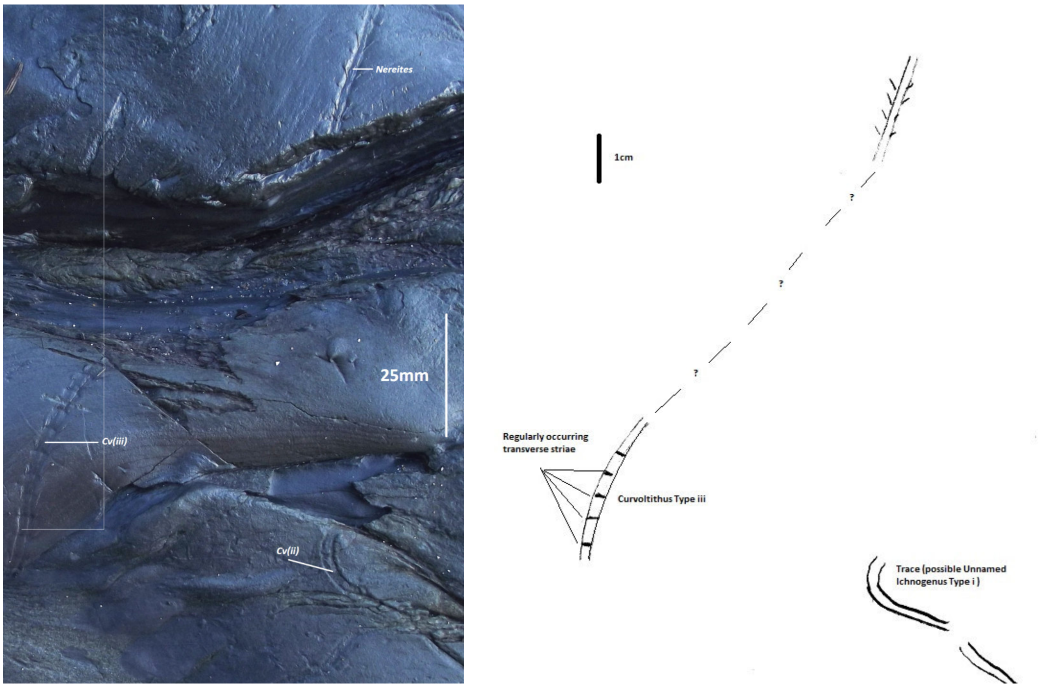


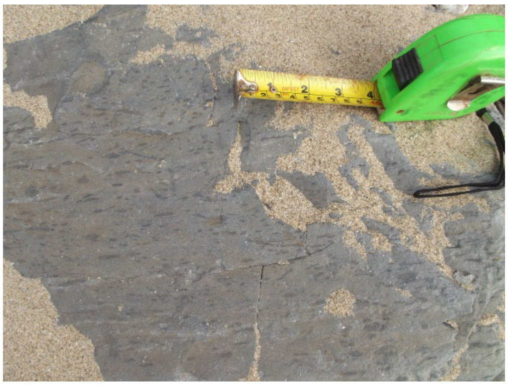
Figure 5.6: *Curvolithus* Variation Type (iii) together with further nerietid traces. All surficial bedding plane occurrences, Cilborth Beach. The dotted line indicates the possibility that the Nereites trace and Curvolithus Type iii traces are a result of the same animal's activity and are therefore synonymous, representing variation of locomotion manner, depth of registration, or substrate characteristics.

5.2 *CHONDRITES*

Ichnogenus: *CHONDRITES* (von Sternberg 1833)

Ichnospecies: *CHONDRITES* Type i

Mode of preservation: Endichnial
Occurrence: Burrow Mottled Member of the Nantmel Formation (presumed *anceps* biozone), Traeth Penbryn (SN292523).
Description:
Elliptical / ovoid burrows, dark grey burrow fill within a pale grey thickly bedded MUDSTONE. Typically 3-4mm maximum diameter, exceptionally up to 10mm, length dependent on section orientation



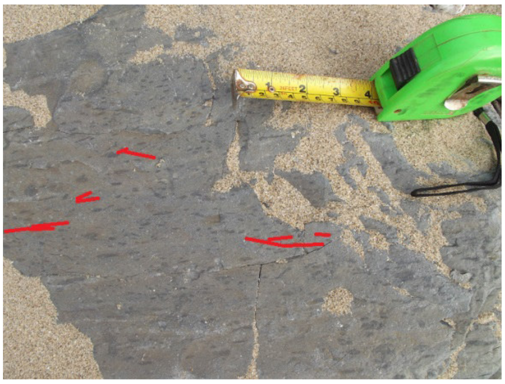


Figure 5.7: *Chondrites*; Divergent branching burrows shown with red overprint. Majority of the traces are seen as cut through vertical sections. No apparent crossing of traces therefore evidence of phobotaxis by trace maker.

Ichnogenus: *CHONDRITES* von Sternberg 1833

Ichnospecies: *CHONDRITES* Type ii

Mode of preservation: Endichnial
Occurrence: Mottled Mudstone Member at the base of the Cwmere Formation (*persculptus* biozone)

Description: Dark grey, unlined, almost circular, ovoid burrows associated with slightly paler grey mudstone horizon. Individual burrows up to 8mm diameter.

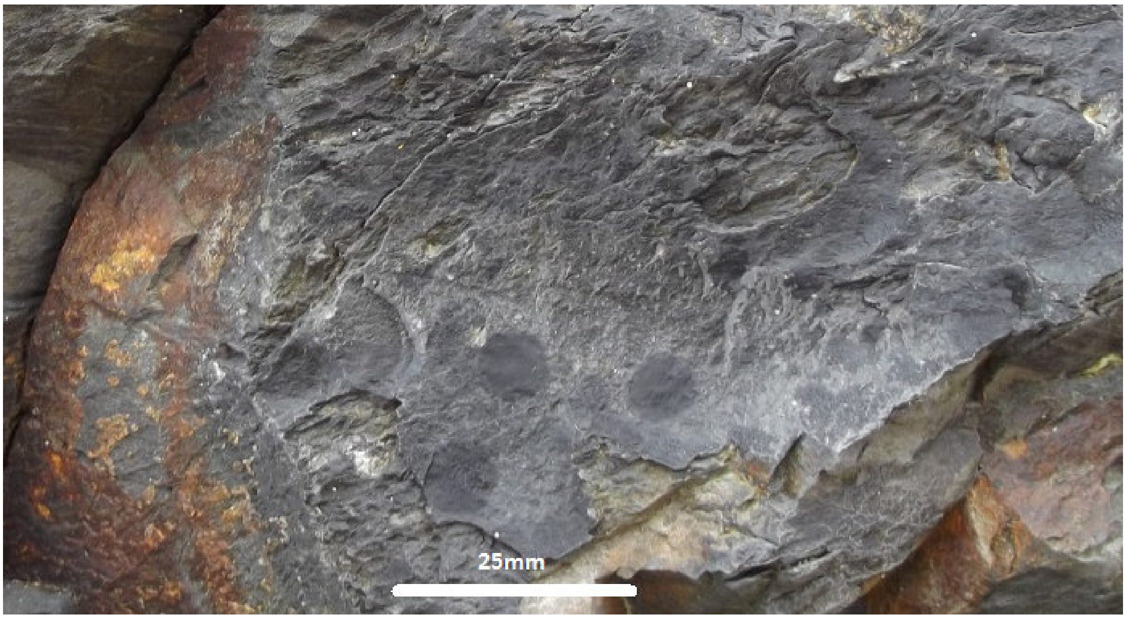


Figure 5.8: *Chondrites* from the Mottled Mudstone Member(Pendinaslochtyn). Occurs only a few metres stratigraphically below the first occurrence of recovery fauna represented by graptolites and orthocones in the Cwmere Formation.

5.3 *CRUZIANA*

Ichnogenus: *CRUZIANA*

Ichnospecies: c.f. *Cruziana acacensis* (Seilacher 2007)

Figure 5.9; *Cruziana* (Traeth Carreg-y-ty)

Mode of preservation: Negative semi-relief on base of bedding planes. Aligned feeding burrows typically 150mm long and circa 50mm wide. Indicative of trilobitoid feeding burrow activity. Diagnostic cruzianid bilobed appearance is only intermittently seen, but the endopodal longitudinal stratch marks typical of *Cr. ac.* are seen in places

Occurrence: Single occurrence in fallen boulder from Brynglas Formation at Traeth Carreg-y-ty (SN300536).

Scale rule is 150mm in length.

5.5 *PARAHAENTZSCELINIA?*

Ichnogenus: Tentative assignment to *Parahaentzschelinia?* Chamberlain, 1971, associated with *Chondrites* (Type 1) von Sternberg 1833 and *Thalassinoides*?-)

Ichnospecies: *indeterminate*

Mode of preservation: Endichnial Full Relief

Occurrence: Burrow Mottled Member, Nantmel Mudstone Formation, Traeth Penbryn (SN 294527)
Description: Inverted conical structure, disrupting local bedding. Bedding is displaced upwards on the outside of the structure, and above, but displaced downwards and disturbed / disrupted within the conical structure. Up to 380mm height, and up to 100mm across. The base of the cone structure is associated with a horizon of dark grey *Chondrites* (Variation Type 1). and *Thalassinoides (?).*

Original Photograph Annotated Image

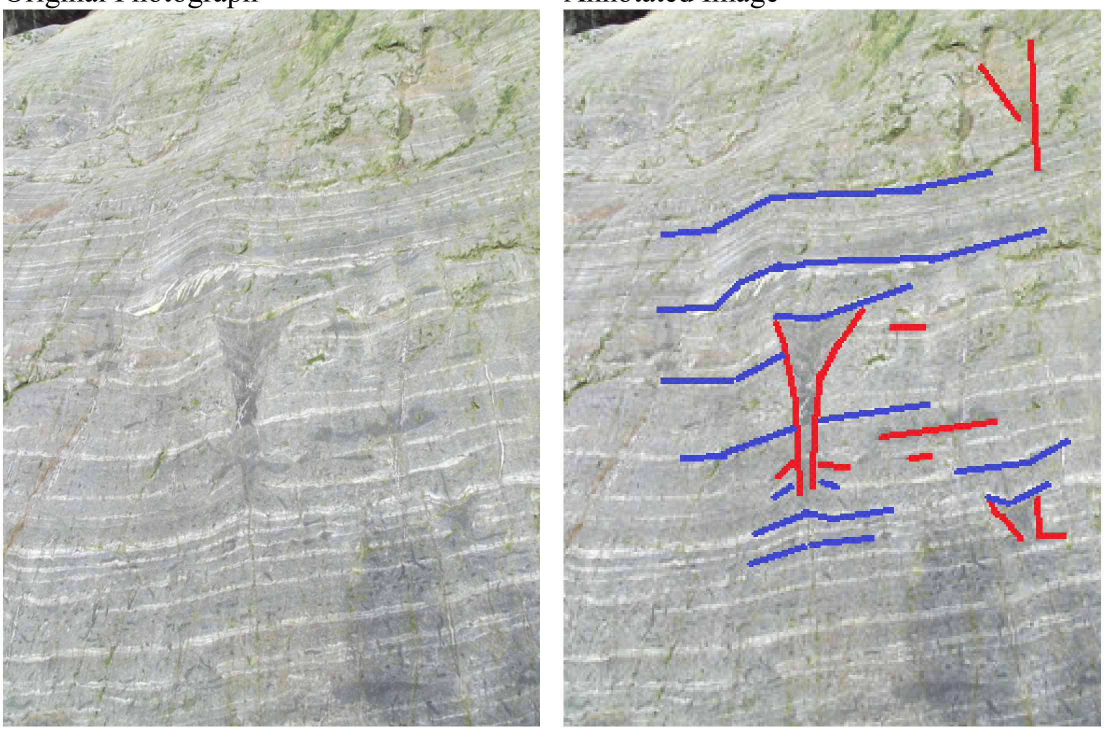


Figure 5.10: Inverted cone structures and associated *Thalassinoides* igen. burrow systems outlined in red. Disrupted primary bedding fabric shown in blue. The density of the *Chondrites* igen. fabric decreases vertically in this section. Field of view approx. 1m X 1.5m.

Alternative explanations for the origin of the inverted cone structure include possible dewatering or degassing structures (similar to those assigned to *Medusinites aff.* in the Ediacaran, but recently shown to be pseudofossils (Menon, McIlroy et al 2015)).

5.6 *MEROSTOMICHNITES / DIPLICHINITES*

Ichnogenus: *Merastomichnites* (Packard 1900)

Ichnospecies: *indeterminate*

Mode of preservation: Epichnial semi-relief
Occurrence:
(1) Cilborth Beach, Llangrannog, SN312544 (Trace Fossil Horizon) Brynglas / Drosgol Formation
(2) Fallen boulder Carreg y Ty SN300534
(3) Llangrannog Main Beach (adjacent to Beachside Café) SN310542
(4) Coastguard Station Car Park on coastal Footpath) SN312542

Description: Trackway formed from a double row of transversely orientated imprints. Trackway is typically gently meandering. Trackway is typically 20-25mm across but can be up to 40mm wide, with each print up to 9mm long (measured oblique to presumed movement direction). Individual imprints typically 2-4mm but exceptionally 5-7mm apart.

Merastomichnites differs from *Diplichinites* by the typically oblique relationship between imprint and movement direction of the latter. However, note that some examples demonstrate a transition from oblique to tranverse orientation from right to left across the image. This is a somewhat arbitrary distinction however, and the occurrence from the Beach Café location (above) should be assigned directly to *Diplichinites.*

Figure 5.11 Paired trackway, Cilborth Beach.

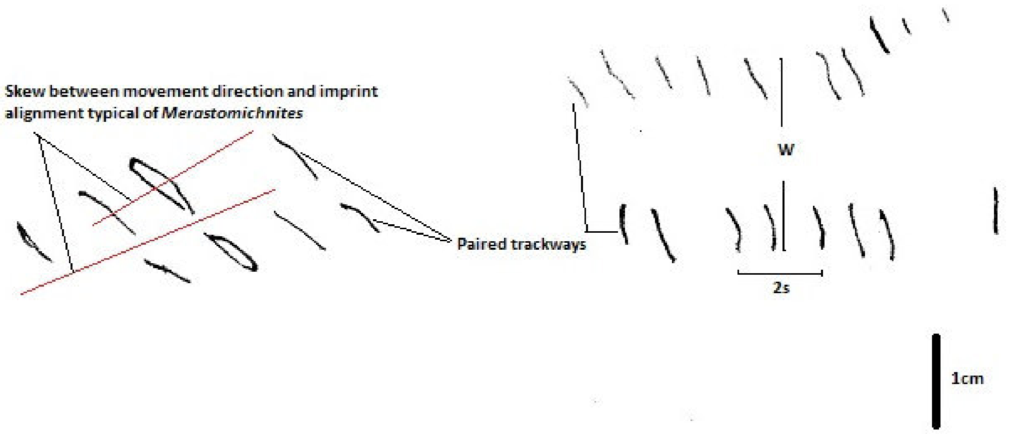


Figure 5.12 Paired trackway, Cilborth Beach, note that the track imprints are not aligned perpendicular to the movement direction on the left-hand side of the trackway.

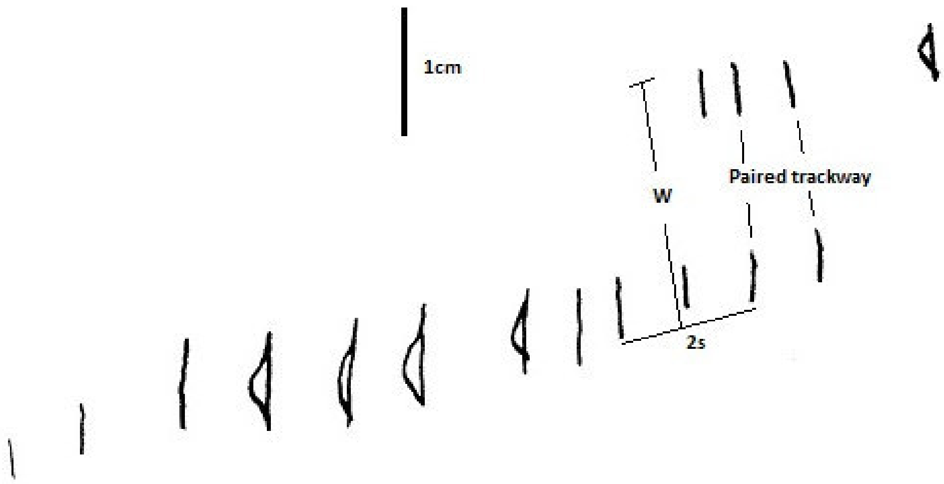


Figure 5.13 Paired Trackway, Cilborth Beach

Figure 5.14: ***Diplichinites*** **from Beach Front Café exposure, Llangrannog. High skew angle between apparent movement direction and individual track alignment, indicative of "ferry glide" type locomotion across a head current.**

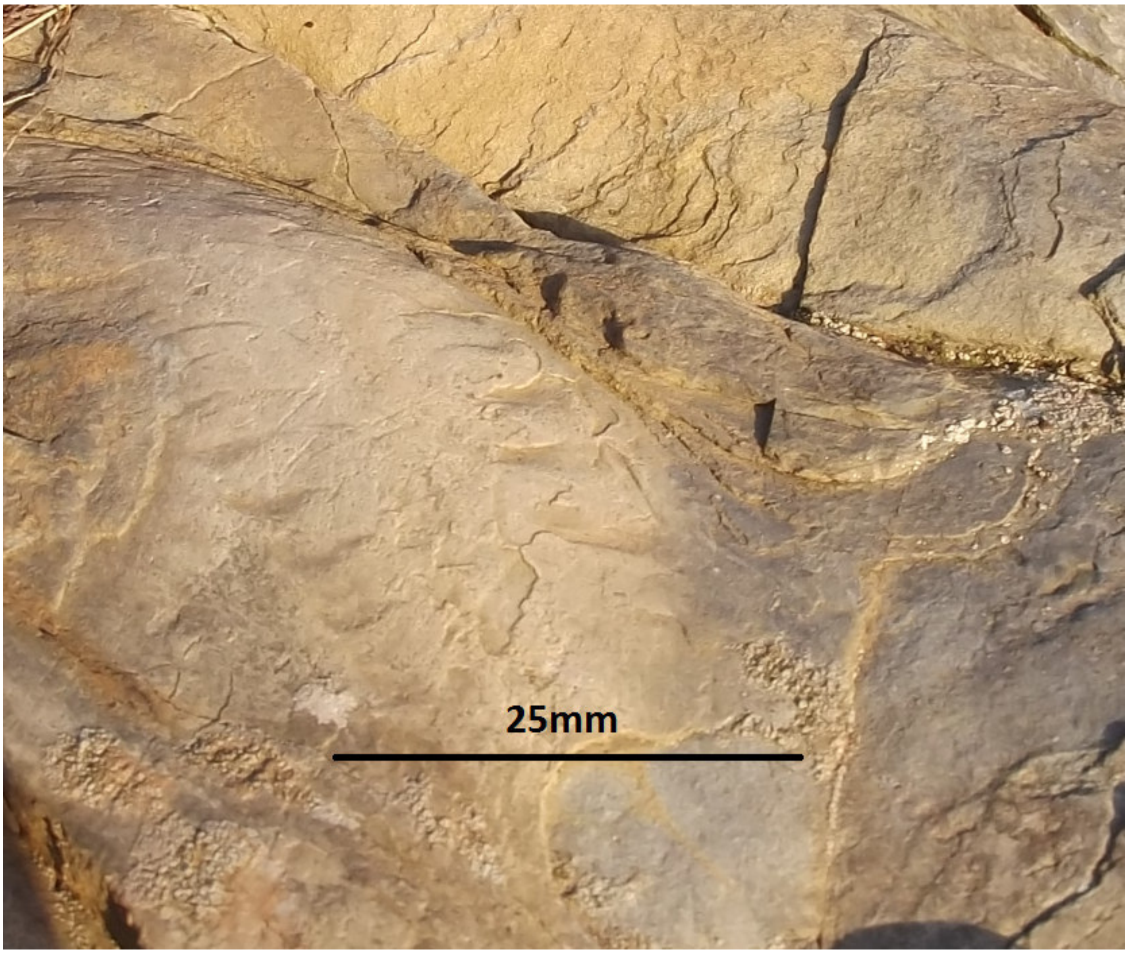


Figure 5.14a: ***Diplichinites*** **from Coastguard Car Park (highest stratigraphic occurrence) Uppermost Brynglas Formation**

These traces are suitable for numerical description to aid definition of potential ichnospecies within the ichnogenera. The track width (w) is a relatively easy metric to establish (measured as a maximum value, perpendicular to the apparent movement direction. The two stride dimension (2s) is similarly relatively easy to define, represented by a typical distance between three consecutive strides, as defined in the sketch below:

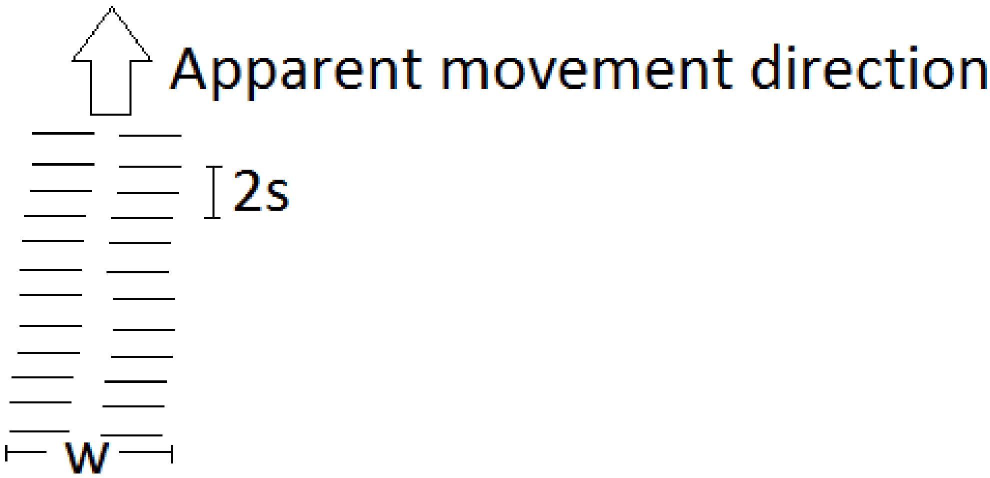


Figure 5.15 Definition of track width and two stride dimension metrics

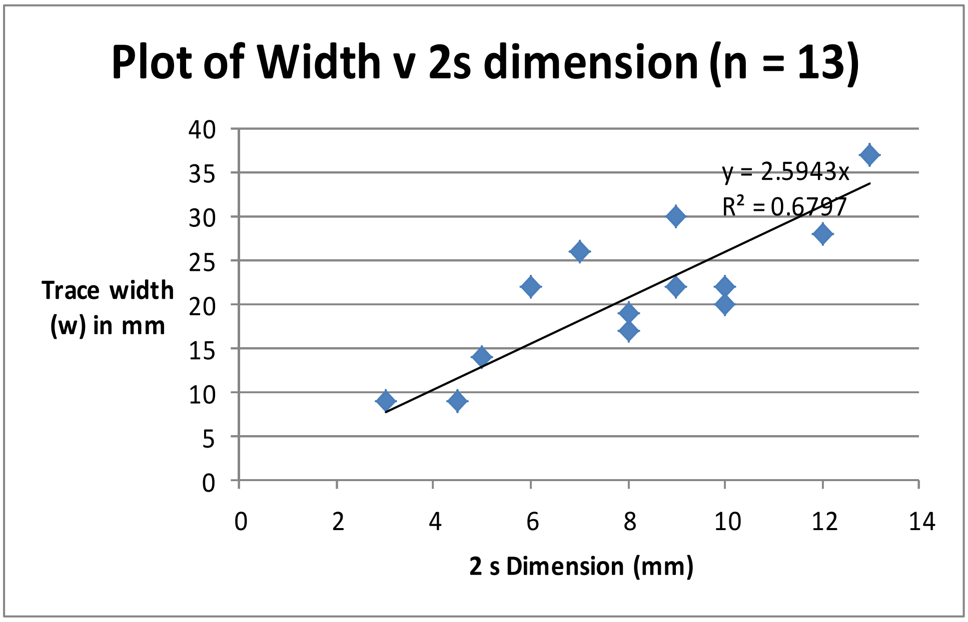


Figure 5.16 Width v 2 stride dimension

The track width varies from 3mm to almost 40mm width but with a reasonably uniform and consistent ($R^2 = 0.68$) ratio of 2.6 between the two--stride dimension and the trace width.

Osgood published a number of detailed images of related traces from the Upper Ordovician of the Cincinnati area (Osgood 1970) and the following comparison of the W/2s ratio can be made from Osgood's Figured specimens:

Allocotichnus dyeri Figure 2 Plate 72 W/2s =1.0
Asaphoidichnus trifidum Figure 1 Plate 73 = 1.1
Trachomatichnus numerosum Figure 3 Plate 73 = 2.7
Petalichnus multipartitum Figure 5 Plate 73 = 3.0

Petalichnus multipartitum Figure 6 Plate 7.3 = 3.5

Similarly Figure 2.13 includes tracks assigned to *Hymnocaris* by Salter – these display a W/2s ratio of 3.3.

5.7 *NEREITES*

Ichnogenus: *Nereites* (MacLeay 1839)

Ichnospecies: Variation Type i, aff. *N. sedgwicki (*Murchison *1839)*

Mode of preservation: Epichnial semi-relief
Occurrence: Cilborth beach, Llangrannog SN312544, Brynglas Formation

Description: Straight to gently meandering furrow between 6mm and 13mm across. Lateral ridges form almond shaped peds of discarded material. Well preserved specimens that are straight show the lateral peds to be paired.

Figure 5:17: Two adjacent occurrences of *Nereites* (Type i), Cilborth Beach.

The W/2s ratio can also be applied to this ichnospecies. The two occurrences above yield W/2s values of 0.89 (the larger occurrence) and 1.0 (the smaller example).

Ichnogenus: *Nereites* Macleay, 1839

Ichnospecies: Variation Type ii, c-f. *N. sedgwicki (*Murchison, 1839)

Mode of preservation: Epichnial semi-relief

Occurrence: Cilborth beach, Llangrannog SN312544, Brynglas Formation

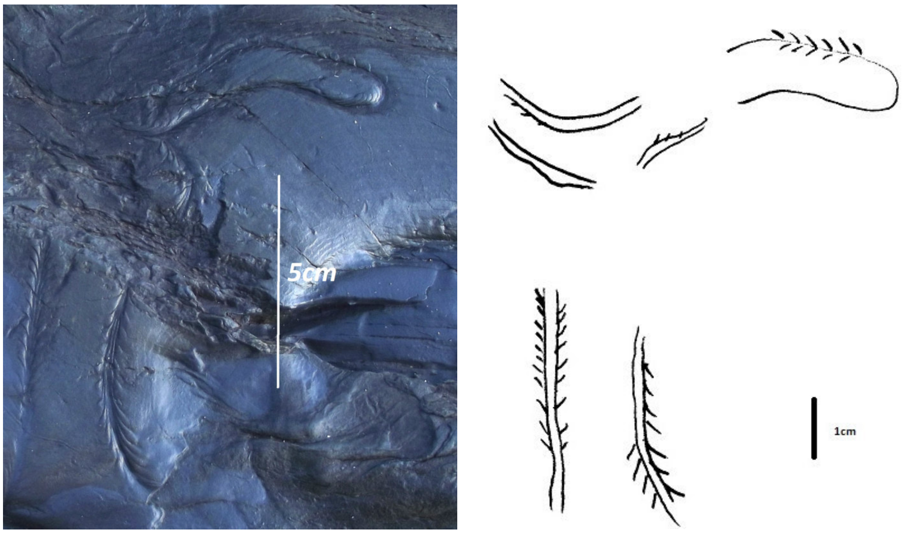


Figure 5.18: *Nereites* Type 1, Cilborth Beach

Description: Biserial deep keel like furrow, typically gently meandering but occasionally seen to turn completely (6-9mm diameter). Does not display phobotaxis with traces crossing. Lateral ridges are deeply incised chevronate features. Can be seen to grade into Type 1 *Nereites* locally Type I .

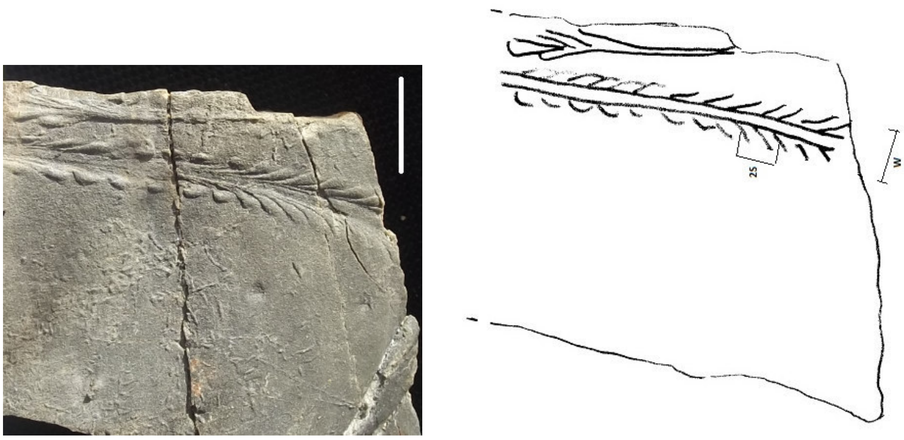


Fig 5.19: Sample Ref: KHN0008, *Nereites* (Type i) merging into *Nereites* (Type ii). Cilborth Beach.

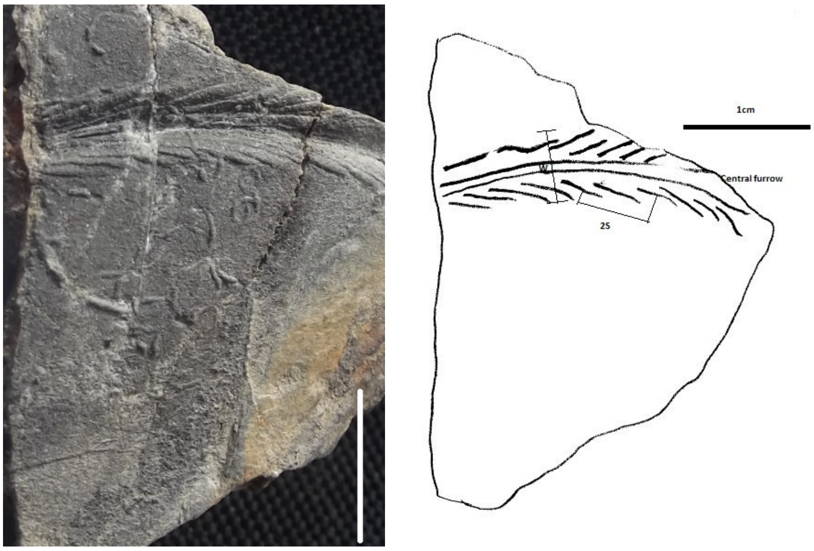


Fig 5.20: Sample Ref: KHN0008, Cilborth Beach

Fig 5.21; Sample KHN0008 In-situ (See Figs 5.19, 5.20)

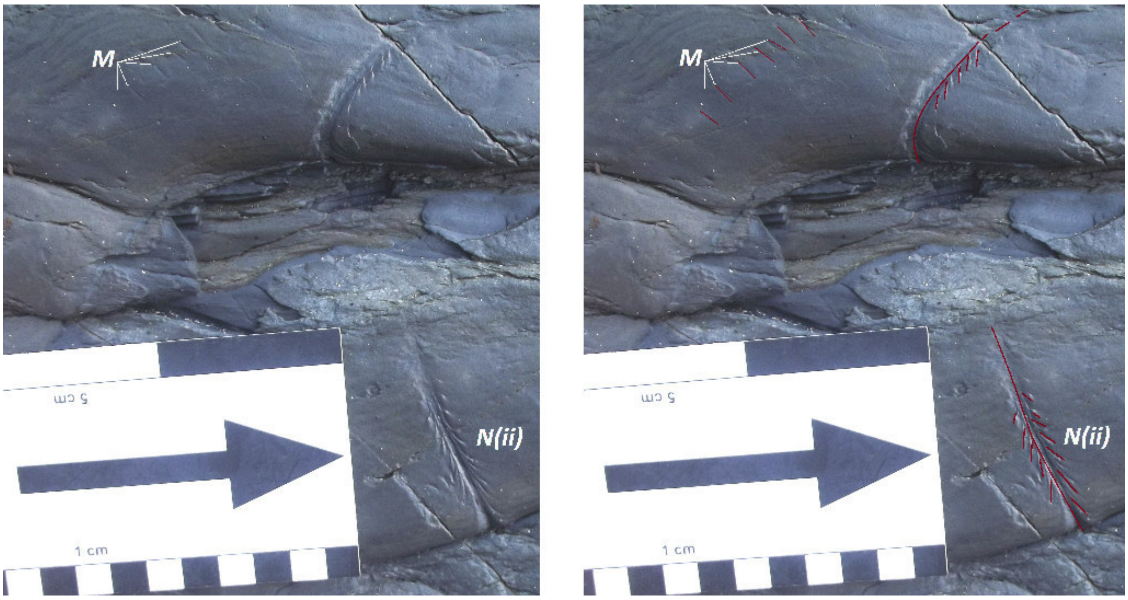


Fig 5.22; *Nereites* (Type ii), Cilborth Beach (Note occurrence of faint *Merastomichnites (M)* to top left). Both occurrences are epichnial traces on bedding surfaces.

5.8 *MEGAGRAPTON*

Ichnogenus: *Megagrapton (Ksiazkiewicz 1968)*

Ichnospecies: aff. *M. irregulare*

Mode of preservation: Hypichnial semi-relief
Occurrence, Allt Goch Formation: fallen block in old quarry adjacent to Brynhoffnant Road

Fig 5.23: *Megagrapton* Left hand image shows undersurface (bedding plane) of fallen block from old quarry in Allt Goch Formation, Llangrannog. Smaller images to right show similar traces from the coeval strata from respectively (top to bottom) Cwm Hirnant, Castell Bach, and Oslofjord. The Castell Bach example is seen in-situ on basal bedding planes. The Solvik Formation is seen on overturned bedding planes.

Branching, anastomosing burrow system. Primary burrows up to 6-8mm diameter. Found on bases of turbidite units.

5.9 *KINNEYIA*

Ichnogenus: *Kinneyia* (Walcott 1914)

Ichnospecies: N/A

Mode of preservation: Epichnial positive relief on bedding surface
Occurrence: In laminated, thinly bedded siltstone above the highest debrite horizon within the Brynglas Formation at Ynys Lochtyn (SN 312 551).

A single occurrence within the Foel y Ddinas Formation of Cwm Hirnant may represent a destruction feature of Kinneyia or similar microbial mat (Sample Ref: KHN 0036)

Fig 5.24: Algal mat, Pendinaslochtyn. The scale bar is 150mm long and lies alongside a series of irregular but generally sub-parallel (occasionally bifurcating) ridges 2-3mm high and up to 20mm between ridge crests. In this image the ridges are well defined by shadows from a low evening sun

Figure 5.25: Algal? mat from Traeth Lochtyn, Llangrannog. Series of pits and blisters (pink colouration) overlain by a (pale green tinged) finely rippled biofilm. Diameter of Marker Pen is 15mm.

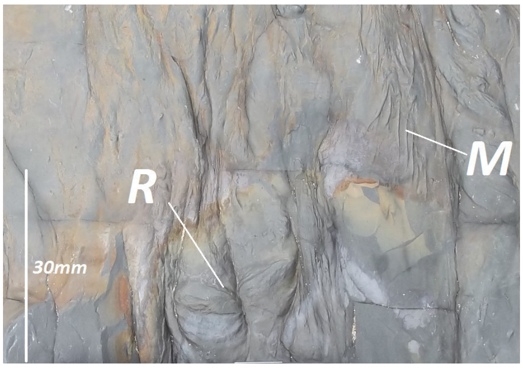
Description:
Related to trace fossils, but not the "work of an animal" these "elephant skin" structures are thought likely to represent biogenic films or mats. They include a range of characters as a consequence of the method of formation, the environment during growth, the style of subsequent erosion / death and "post-mortem" influences including weathering and diagenesis. Algal mats are frequently responsible for binding mud, silt and sand surfaces, allowing preservation of detailed sedimentary structures, and they are frequently associated with preserved palimpsest ripples, which have been assigned to the "ichnogenus" *Kinneyia.*

5.10 *RUSOPHYCUS*

Ichnogenus: *Rusophycus* (Walcott 1914))

Ichnospecies: N/A

Mode of preservation: Epichnial negative relief on overturned basal bedding surfaces
Occurrence: Brynglas Formation at Traeth Carreg-y-ty (SN300536).



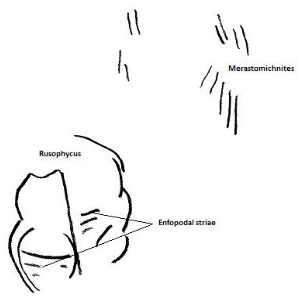


Figure 5.26a: *Rusophycus* (R)

Note association with *Merastomichnites / Diplichinites* (*M*) trace to top right

Approximately 30mm long by 25mm wide sub-ovoid resting trace.

Mode of preservation: Epichnial epirelief on bedding surface on fallen block of Brynglas Formation. Note partial registration (overprint) with *Merastomichnites / Diplichinites*

Occurrence: Brynglas Formation at Traeth Carreg-y-ty (SN300536).

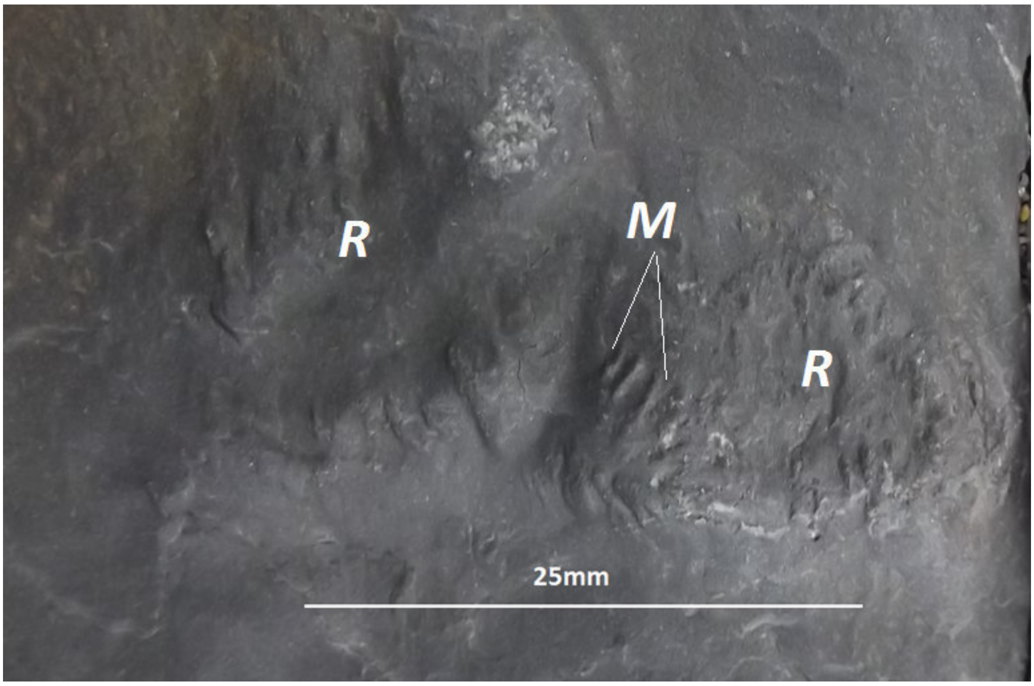


Figure 5.26b: ***Rusophycus (R)*** **and associated (registered)** ***Merastomichnites*** **traces. Considered representative of (respectively) resting and locomotion activity.**

Mode of preservation: Epichnial epirelief on same bedding surface on fallen block of Brynglas Formation as 5.26b

Occurrence: Brynglas Formation at Traeth Carreg-y-ty (SN300536).

Figure 5.26c: ***Rusophycus:*** **preserved resting trace on bedding surface. Overall farm and shape is consistent with trilobite type -trace maker.**

5.11 *TOMACULUM*

Ichnogenus: *Tomaculum* (Groom 1902)

Ichnospecies: N/A

Mode of preservation: Epichnial positive relief on bedding surface
Occurrence: In laminated, thinly bedded siltstone immediately above the highest debrite horizon within the Brynglas Formation at Ynys Lochtyn (SN 313551)

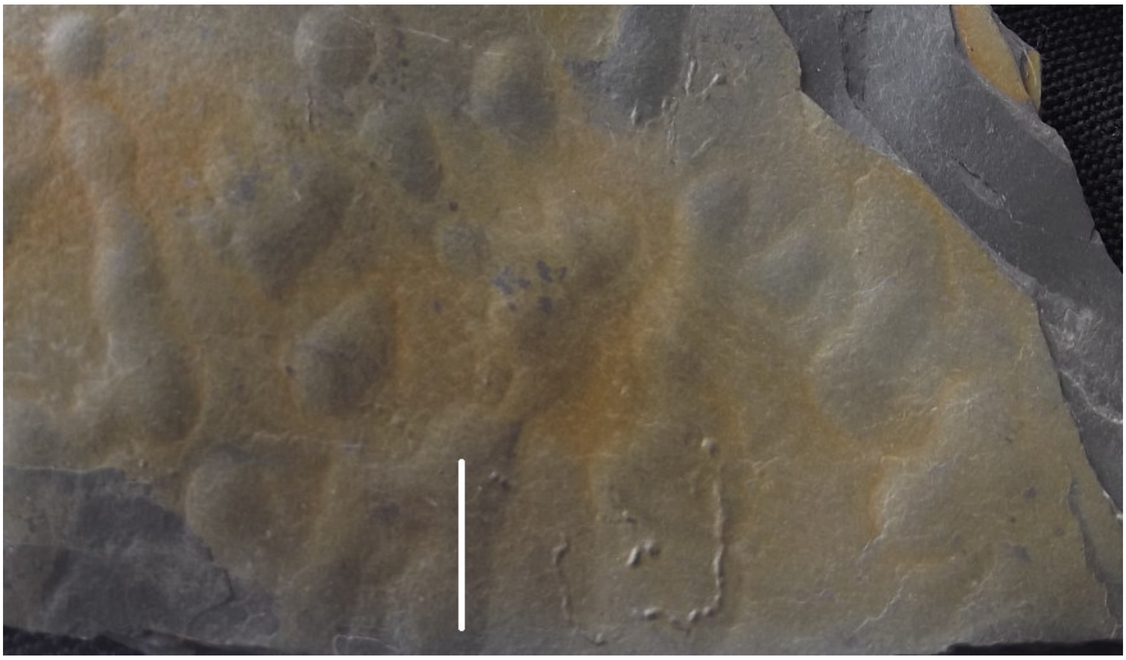


Figure 5.27: Trail of suspected fecal pellets, note also blistered surface indicative of biofilm material

Description:
Related to trace fossils, but not the "work of an animal" trail is thought to represent the faecal pellets / coprolites of an unidentified producer. Individual pellets up to 1mm long, elongate. Associated with a "blistered" surface thought likely to be associated with a biofilm.

5.12 *GORDIA*

Ichnogenus: *Gordia* (Emmons 1844)

Ichnospecies: indeterminate

Mode of preservation: Partial epichnial and exposed hypichnial positive relief on bedding surfaces
Occurrence: Single occurrence of whole system identified from Brynglas Formation at Pendinas Lochtyn headland, Llangrannog, although associated main burrow drive (140mm long) with possible eroded feeding trail encountered within Brynglas Formation, Cilborth Beach.

Description:

Published descriptions of *Gordi*a relate only to the "horizontal scribbles" of the meandering grazing burrow system. These are typically 1mm diameter, and appear not to follow any systematic grazing strategy (described by Seilacher as"sloppy version of planar spirals"(Seilacher 2007)). This occurrence of the Pascichnia, together with the associated Dominichia (dwelling trace) is believed to be unique.

The Dominichia trace apparently links to an epibenthic "portal". This "access drive" is of a slightly larger diameter than the grazing trails, and displays a convex upwards base (this may be a post mortem response of the substrate to "heave" of the burrow floor. The main drive also shows a distinct sub mm scale cross drive direction annulation,

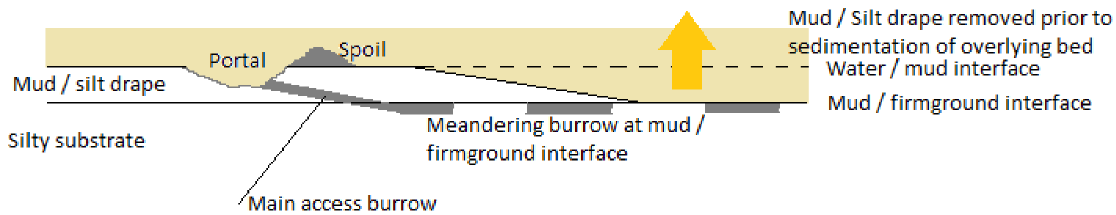


Fig 5.28: Illustration of the architecture of the *Gordia* trace fossil

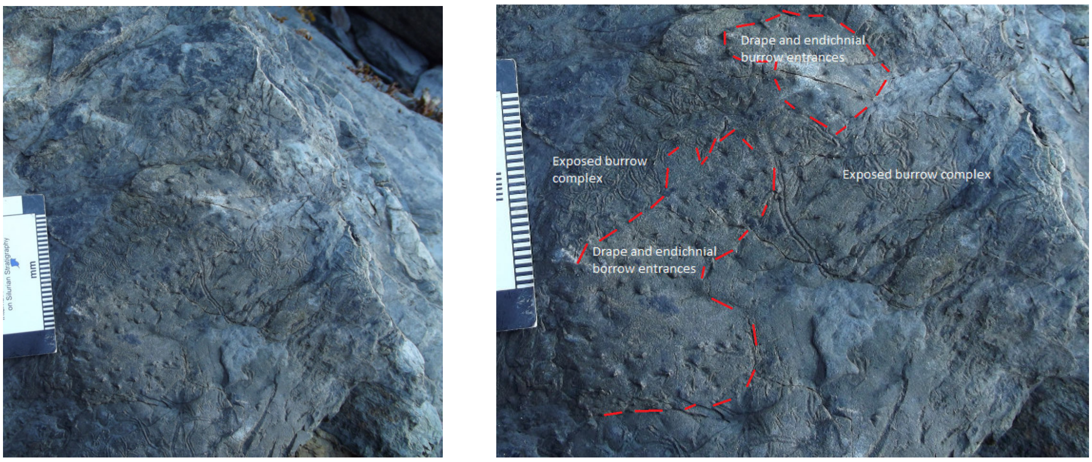


Figure 5.29 ***Gordia*** **undermat mining complex with burrow complex of small "scribbling" traces, access drive and silt drape surface (red) with portal pit and cast features**

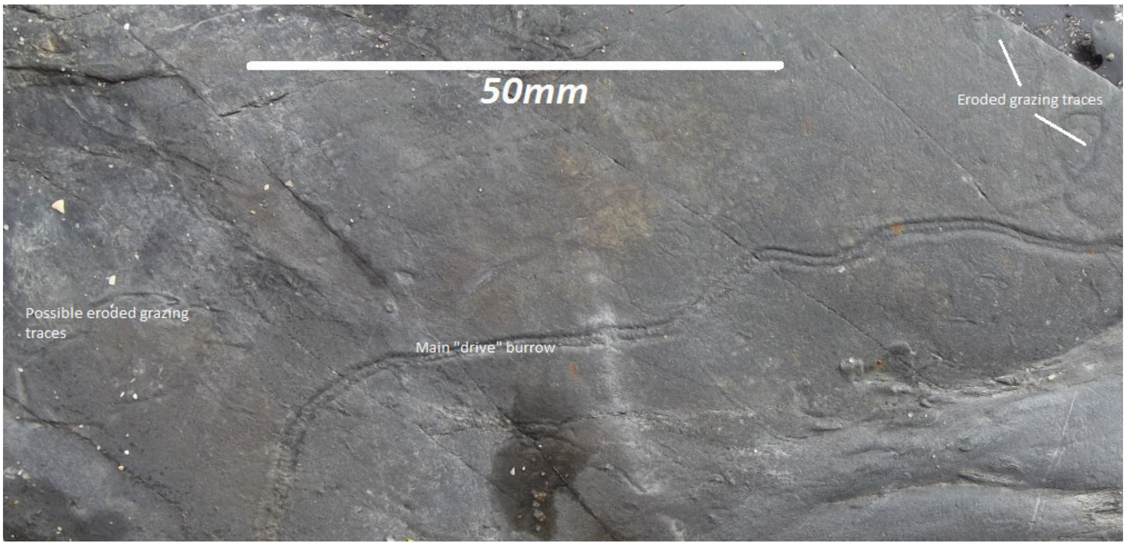


Fig 5.30: Access "drift" passage with faint undertrack "*Gordia*" galleries. Cilborth Beach

5.13 Unnamed ichnogenus (i) c.f. *THALASSINOIDES*

Ichnogenus: cf. *THALASSINOIDES* (Ehrenberg 1944)

Ichnospecies: N/A

Mode of preservation: Hypichnial burrow systems on undersides of bedding, in sequence of turbidite siltstones.

Occurrence: Identified at two locations. KHN0041 from an approximately 30m long outcrop at base of cliffs Traeth Carreg Ifan, Ynys Lochtyn (SN313551) and on Ynys Lochtyn headland at (SN312551).

Description: Horizontal network of sub-cylindrical burrows. Frequent branching, but no apparent crossing of pre-existing burrows (ie seem to be responding to phobotaxis). Differs from standard *Thalassinoides* in that the extent of burrowing incorporates 100% of the substrate. Burrows vary between 1.0 and 1.5cm diameter. No vertical shaft structures apparent

Figure 5.31; Sample Ref KHN0041 – burrow diameter typically 10-13mm

Figure 5.32: ***Thalassinoides*****? Ynys Lochtyn, Llangrannog – burrow diameter typically 6-8mm**

5.14 *PLANOLITES*

Ichnogenus*: PLANOLITES* (Nicholson 1873)

Ichnospecies: N/A

Mode of preservation: Endichnial burrow within turbidite siltstones.

Occurrence: Identified at single location in youngest Brynglas Formation (Coastguard Station Car Park on coastal Footpath) SN312542

Fig 5.33: *Planolites*, Upper most Brynglas Formation (co-occurrence with Fig 5.14a Diplichinites)

Description: Single sub-horizontal lined burrow up to 3mm diameter. Curving upwards and cross cutting bedding.

5.15 Unnamed *Ichnogenus (ii)*

Ichnogenus: Unnamed

Ichnospecies: N/A

Mode of preservation: Epichnial positive relief on bedding surface
Occurrence: Single occurrence identified from the Brynglas Formation, Cilborth Beach, Llangrannog (SN312544).

Description:

Short, straight trail, approximately 4mm width, up to 2.9cm long. Takes the form of a flat based furrow, with regularly spaced nodes in the side walls, and associated small (sub mm) ejectemanta paired peds on the surrounding substrate surface

Figure 5.34: A single occurrence of this unnamed ichnogenus, from Cilborth Beach, Llangrannog. Paired sequence of lateral peds suggests related to Curvolithus, but significantly smaller than other examples of that ichnotaxa.

5.16 Unnamed Ichnogenus (iii)

Ichnogenus: Unnamed

Ichnospecies: N/A

Mode of preservation: Hypichnial positive relief on undersole of distal turbidites.
Occurrence: Single occurrence identified at Llangranog Main Beach (SN309542).

Description:

Collection of small short burrows, sub mm scale in diameter – up to 6mm long, occasionally branching at acute angles, diameter of burrows vary along their length, generally greater width in the middle of the burrow. This implies that the burrow may be curving vertically from the base of the turbidite, back toward the main body of the sediment. Reminiscent of “thready ridges & knobs” seen on much younger (Cretaceous / Tertiary) turbidite soles associated with low levels of oxygenation Leszczynski (1991).

Figure 5.35: Sample No: KHN0015 shows underside of a bedding plane associated with a turbidite sole developed within the Brynglas Formation (Llangrannog Beach, southern cliff).

5.18 Unnamed Ichnogenus (iv)

Ichnogenus: Unnamed

Ichnospecies: N/A

Mode of preservation: Endichnial positive surface relief on bedding planes.
Occurrence: Single occurrence identified from the Brynglas Formation, Cilborth Beach, Llangrannog (SN312544).

Description: circa 80mm long straight trace approximately 8mm wide, comprising a medial linear raised axis, with paired peds of lateral ejectementa. The width v 2s dimension value is a fraction in this case (approximately 0.5).

Fig 5.36: Unnamed ichnogenus preserved unusually as positive relief on bedding surfaces. Cilborth Beach. Paired peds of ejectementa to side of trace associated with a single linear ridge.

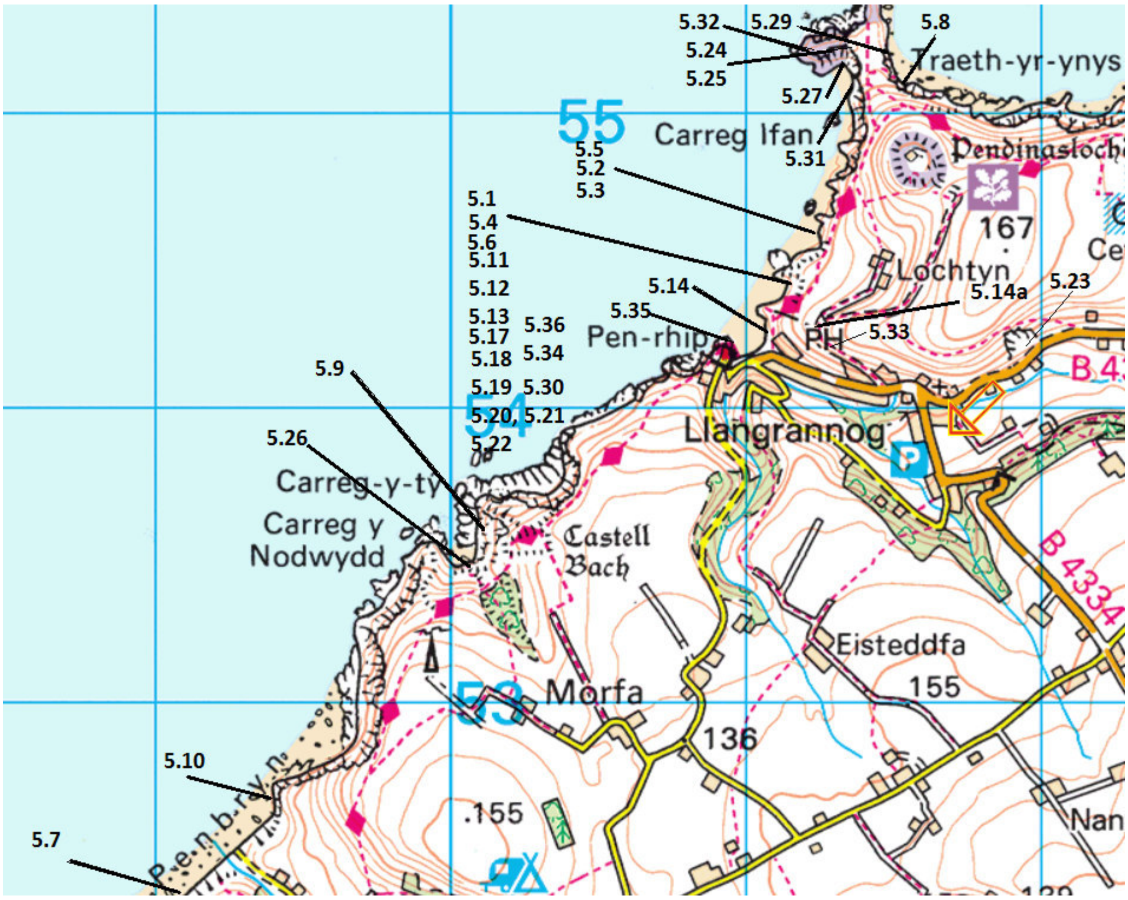


Fig 5.37: Locations of figured specimens (Base map: Streetmap.co.uk)

5.19 Ichnofaunal Diversity

Table 5.1 below shows the relative abundance of ichnogenera identified and described in the Llangranog succession. It is apparent that ichnofaunal diversity cannot be directly correlated with standing ecological diversity expressed in standard models of extinction processes around the end Ordovician Mass Extinction. These would suggest that peak standing diversity would be anticipated in the pre-extinction i.e. in the Nantmel Formation, and post extinction intervals (the Cwmere Formation and the Allt Goch Formation).

On the contrary peak ichnofaunal diversity (9 no.) is associated with the Brynglas Formation, as is (somewhat paradoxically) the minimum ichnodiversity seen in the Drosgol Formation (Figure 5.38).

Table 5.1: Ichnofaunal abundances in the Llangrannog Succession

Formation	Listing
Allt Goch Formation	*Megagrapton*
Cwmere Formation	*Planolites* *Chondrites* (Type 2)
Brynglas Formation	*Curvolithus* *Cruziana* *Merastomichnites / Diplichinites* *Kinneyia* *Rusophycus* *Tomaculum* *Gordia* Unnamed Ichnofauna cf *Thalassinoides* Unnamed Ichnofauna ii Unnamed Ichnofauna iii Unnamed ichnofauna iv
Drosgol Formation	No trace fossils confirmed
Nantmel Formation	*Chondrites* (Type 1) *Parahaentzschelinia?* *Thalassinoides* ?

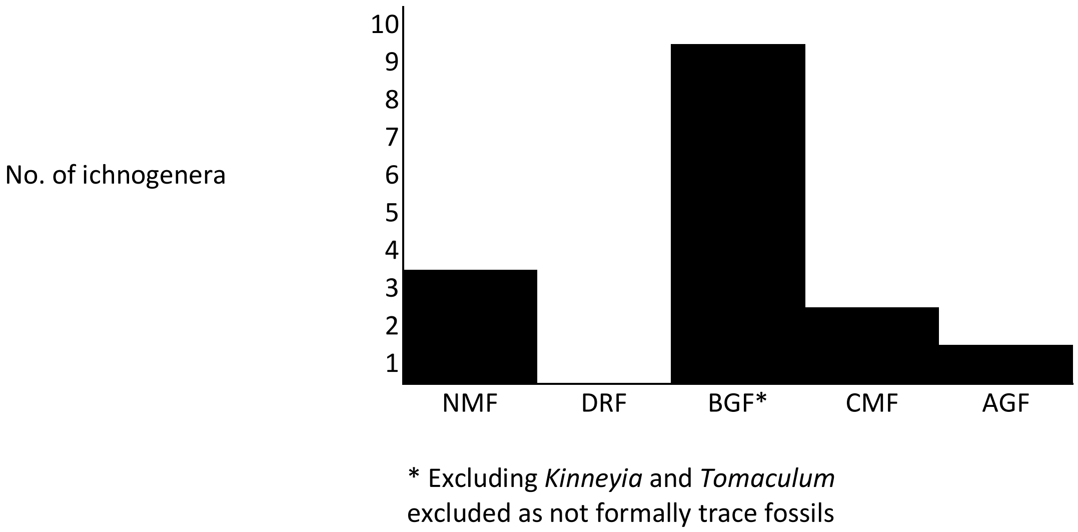


Figure 5.38 Graphical representation of the Ichnogenera Count for the Llangrannog Succession. NMF – Nantmel Mudstone Formation, DRF – Drosgol Formation, BGF – Brynglas Formation, CMF – Cwmere Formation, AGF – All Goch Formation

The minimum ichnodiversity in the Drosgol Formation is considered to be, at least in part, an artefact, and reflects the widespread destruction of much of the primary sedimentary architecture during the liquefaction of this sandy formation associated with the postulated slope failure of the overlying Brynglas Formation.

Considering the ichnospecies identified within the Brynglas Formation as a collective ichnocoenose is revealing. There are 9 clear ichnogenera and 2 additional related features (*Kinneyia* and *Tomaculum*), but this is clearly a somewhat aberrant group of trace fossils.

5.20 Substrate and Tiering

Table 5.2 places the Brynglas Formation within its original sedimentary context, as represented by Goldrings's Substrate Consistency groups (Goldring 1995) and tiering with respect to depth.

We see that the trace fossils present are dominated by shallow burrow (Tier 1) and surface trails (Tier 0) associated with soft ground and loose ground substrates. This is a highly unusual ichnocoenose. It is more usual for the immediate surface material to be represented by a "mixed layer" with little in the way of trace fossils preserved due to substantial over printing by fauna associated with deep burrowing tiers.

This would appear to record a distinct "taphonomic window" associated with the local palaeoenvironment that allowed preservation of the traces left by the epibenthic and shallow benthic fauna as a consequence of the loss / exclusion of deep burrowing fauna that would normally overprint ("register") the soft ground and loose ground traces.

Table 5.2: Ichnofaunal abundances related to Substrate Consistency and Tiering

Substrate Consistency	Ichnogenera (Tier occupancy) (UI – Unnamed ichnogenera)
Soup ground	***Gordia*** **(Portal structures)**
Soft ground	***Curvolithus*** **(Tier 0),** ***Gordia*** **(Tier 0 –Tier 1), UIii, UIiii, UIiv**
Loose ground	***Cruziana*** **(Tier 1),** ***Rusophycus*** **(Tier 1),** ***Merastomichnites*** **(Tier 1), UIi c.f.*****Thallasinoides*** **(Tier 2?)**
Firm ground	***Planolites***
Hard ground, rock ground, shell ground	Absent

This is in contrast to the ichnofauna associated with oxic horizons described in the immediately preceding rocks of the Nantmel Formation (Challands 2008) which comprises an assemblage generated exclusively by soft-bodied organisms that burrowed into the sediment – an infauna (*Chondrites, Thalassinoides, Planolites*, etc). There is no recorded evidence of traces formed by animals (soft or hard-bodied) that lived on the sediment surface or in the water column above. It seems probable that the *Chondrites* animal made an exaerobic living, taking advantage of the presence of sulphate reducing bacteria or archaea at or close to the redox boundary at shallow depth.

Descriptions of “Redox” conditions follow Allinson, Wignall and Brett (1995) as defined In Table 5.3 below:

Table 5.3: Definitions with respect to oxygenation

Description	Definition
Aerobic	**Normal benthic fauna, with no oxygen restriction**
Dysaerobic	**Impoverished benthic fauna, stressed by low oxygen waters**
Anerobic	**No benthic fauna present due to lack of oxygen**
Exaerobic	**Specialised benthic fauna perched between anoxic / dysoxic**
Poikiloaerobic	**Low diversity, opportunistic benthic fauna responding to fluctuating but generally low oxygen conditions**
Oxic	**<1.0 ml/L dissolved oxygen**
Dysoxic	**1.0-0.2 ml/L dissolved oxygen**
Suboxic	**0-0.2 ml/L (low nitrate)**
Anoxic	**0 ml/L**
Euxinic	**0 ml/L (free hydrogen sulphide present)**

Immediately above the highest laminated hemi-pelagite horizon described by Challands et al (2005) are rocks of the lowest Drosgol Formation. Below the first extensive debrite horizon these are extensively burrowed by *Chondrites* and display the shaft collapse structure assigned tentatively to *Parahaentzschelinia.*

The absence of definitive faunal markers makes it difficult to determine whether these structures are representative of the latest Nantmel Formation, or the earliest Drosgol Formation. Nevertheless, they clearly mark a transition from an anoxic environment (the Graptolitic hemi-pelagite horizons with occasional oxic episodes, to a typically sub-oxic environment. This assemblage is represented in Figure 5.39 (below) as the "*Chondrites* Sea" assemblage.

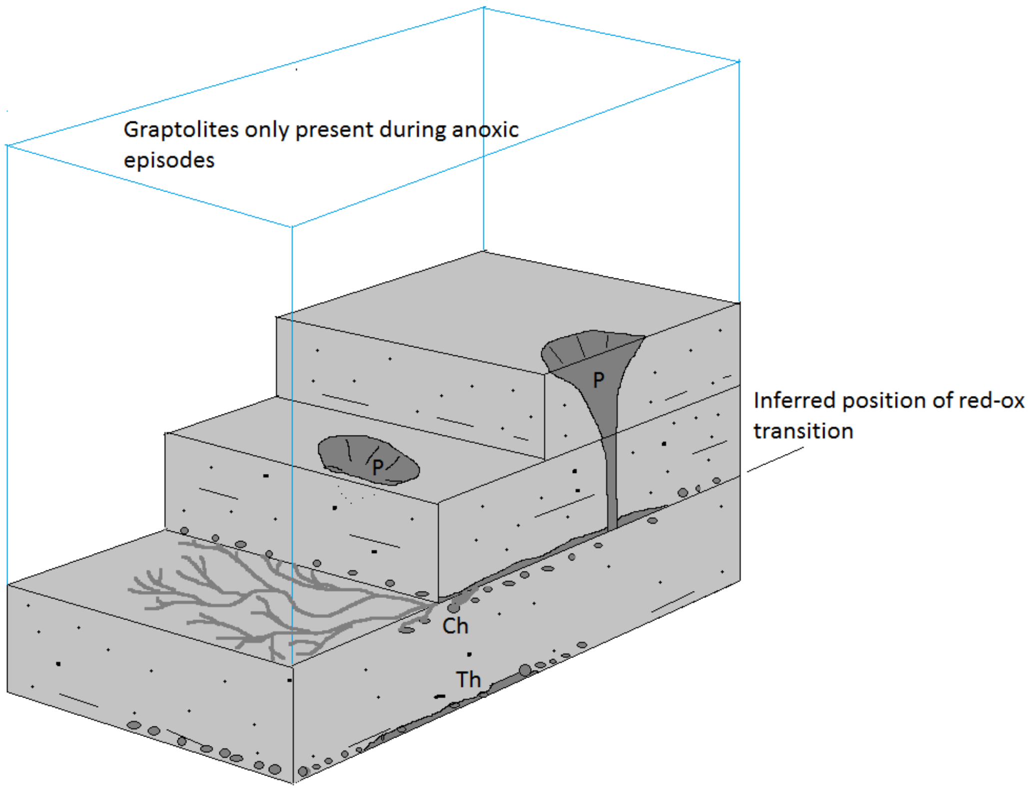


Figure 5.39 The *Chondrites* Sea assemblage Ch = *Chondrites P= Parahaentzschelinia,* Th = *Thalassinoides.*

Nevertheless, the presence of turbidites with “thready ridges and knobs” within the Brynglas Formation, together with the presence of trace amounts of pyrite and occasional pyritic nodules implies that the Brynglas Fomation was probably poikiloaerobic – with fluctuating oxygenation and favouring opportunistic taxa (Goldring 1995). Occasionally conditions were evidently favourable for widespread colonisation by significant sediment processors such as those responsible for the significant reworking seen as the unnamed Ichnofauna (i) (c.f. *Thalassinoides*) and *Cruziana*, and allowing the presence of animals with significant degree of motility (*Diplichinites, Merastomichnites*).

The rocks that are clearly defined as Drosgol Formation by the extensive presence of debrite horizons have not been seen to hold any significant trace or body fossil to date. However, the overlying Brynglas Formation, whilst devoid of any significant body fossil assemblage, shows traces which show, at least intermittently, that throughout Brynglas Formation times, there was a reasonably active, diverse and motile fauna present on, and immediately below, the sea bed. Figure 5.40 shows a simplified representation of the Brynglas Formation assemblage.

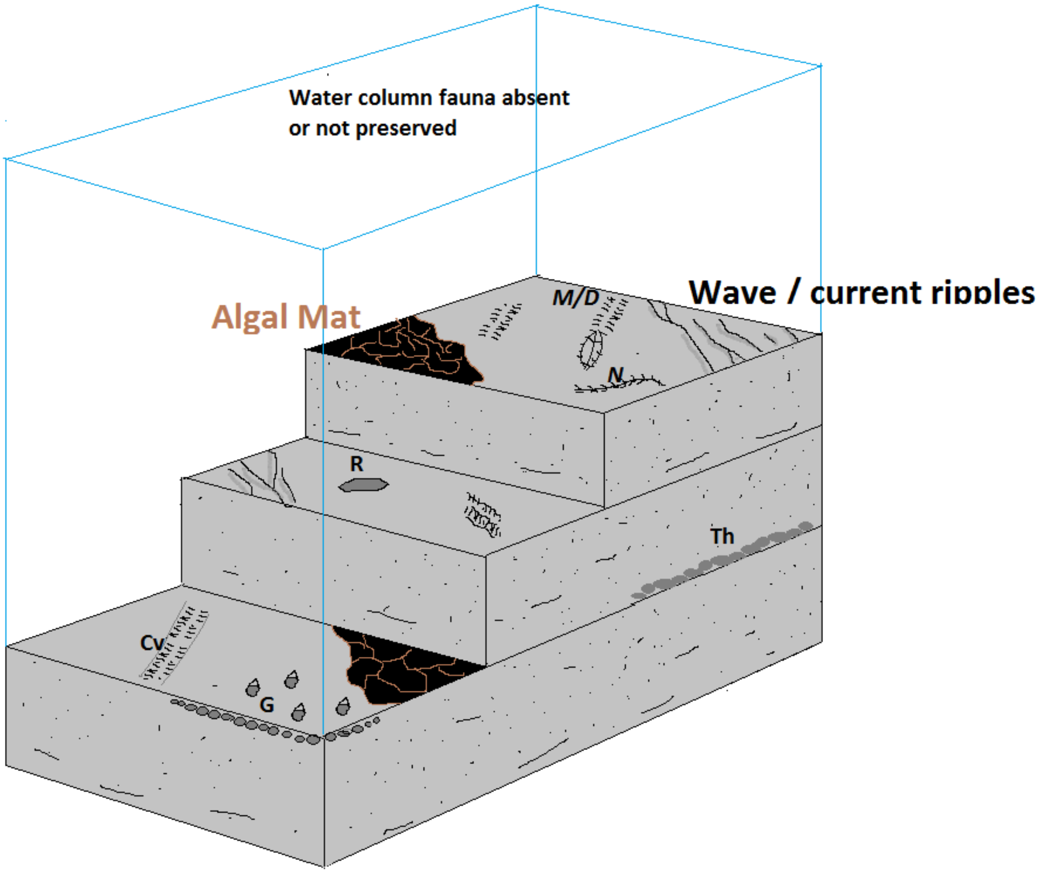


Figure 5.40 The Brynglas Formation assemblage, surface ripples shown at top right M/D = *Merastomichnites/Diplichinites*, G = *Gordia*, Cv = *Curvolithus*, *R = Rusophycus, Th = Thalassinoides?, N = Nereites*

Following the glacial lowstand which appears to have occurred toward the end of the period of sedimentation of the Brynglas Formation, conditions again reverted to a sequence dominated by hemi-pelagite sedimentation with occasional oxic influences. This appears to be associated with the *persculptus* graptolite zone, and the re-establishment of a body fossil assemblage, comprising graptolites and orthocones.

Unlike the transition at the base of the Brynglas horizon there is no broad zone of transition equivalent to the "*Chondrites* Sea" of the earliest Hirnantian, but there is a single discrete event, present at the base of the Cwmere Formation and marked again by the presence of *Chondrites,* seen in the basin wide "Mottled Mudstone Member" proven at the base of the cliffs at Traeth Pendinas Lochtyn. This faunal assemblage is represented in the sketch presented as Figure 5.41, below.

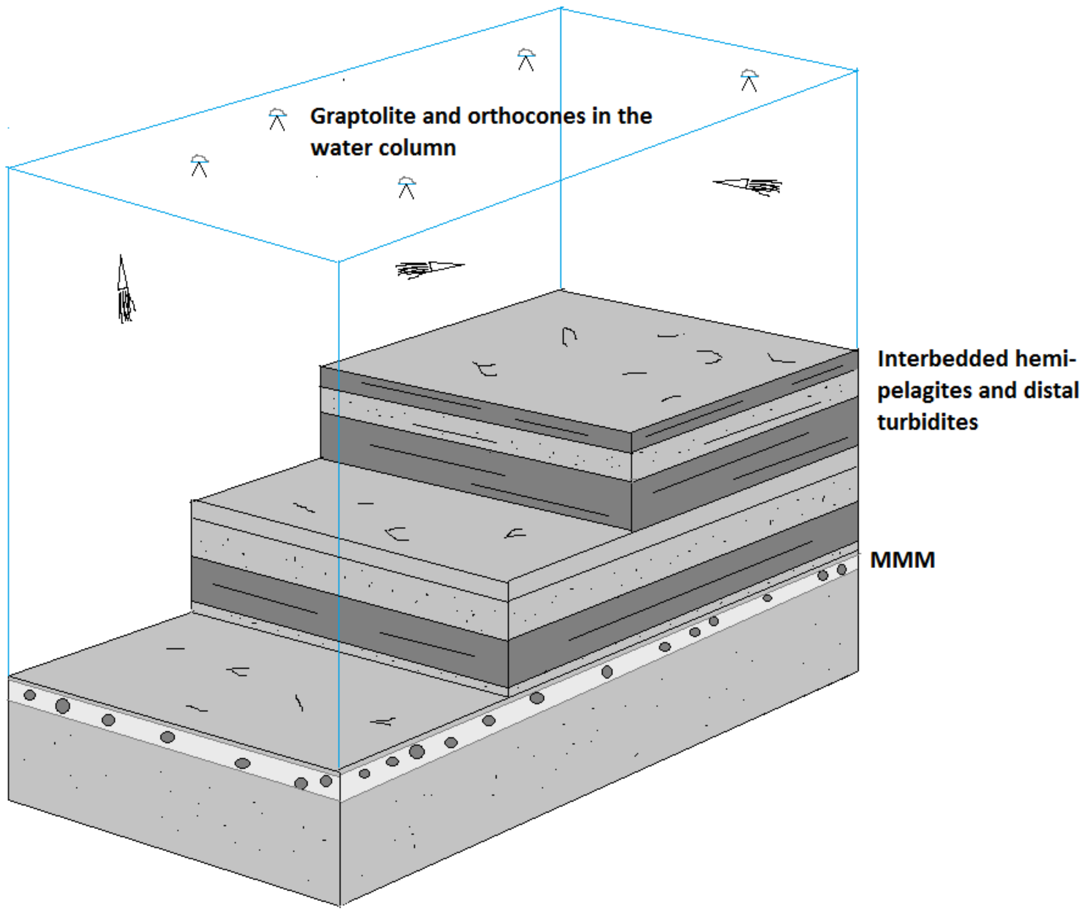


Figure 5.41 The "*persculptus* Sea". The Mottled Mudstone Member (MMM) (see Figure 5.8) represents a basin wide marker horizon after which sedimentation patterns were dominated by turbiditic influences and laminated hemi-pelagites.

This variation in ecospace utilisation can be visualised using a simplified version of techniques developed by Bambach, Bush and Erwin (2007). The original method utilised a three-dimensional matrix allowing representation of Tiering (y-axis), Feeding mode (x-axis) and Motility (z-axis). Given the relatively restricted fauna it is reasonable to omit the Motility and represent the data as a simple plot of Tiering and Feeding mode, as shown in Table 5.4. on the following page.

The table shows how the ecosystem changed through the Hirnantian event with the initial ecosystem including pelagic suspension feeders (graptolites) and deep burrowing infauna, but this ecosystem being replaced by a predominantly surface and shallow burrowing fauna.

The Cwmere Formation sees the return of pelagic suspension feeders, and the first appearance of pelagic predators (orthocones) in the study area. The almost complete absence of surficial and shallow burrowing fauna in both the Cwmere Formation and the

Nantmel Formation is in marked contrast to the dominant modes of life (surficial, semi and shallow deposit feeders and miners) expressed in the Brynglas Formation. Of note in the Brynglas Formation is the absence of demonstrable epichnial grazing activity, which may be one of the causes of an apparent resurgence in the presence of *Kinneyia* and similar algal mat structures.

Table 5.4 Ecospace Utilisation

Nantmel Formation ("*Chondrites* Sea")

	Suspension	Surficial Deposit	Mining	Grazing	Predatory	Other
Pelagic	1					
Erect						
Surficial						
Semi						
Shallow						
Deep			2,12			

1 *anceps* zone graptolites in Laminated hemi-pelagites
2 *Chondrites / Parahaentschelinia*
12 *?Thalassinoides*

Brynglas Formation

	Suspension	Surficial Deposit	Mining	Grazing	Predatory	Other
Pelagic						
Erect						
Surficial		4,14,16			6	7
Semi			8,15			
Shallow			5,13			
Deep						

4 *Curvolithus*
5 *Cruziana*
6 *Merastomichnites/Diplichinites*
7 *Rusophycus*
8 *Gordia*
13 *UI (c.f.Thallassinoides)*
14 *UI (ii)*
15 *UI (iii)*
16 *UI (iv)*

Cwmere Formation ("*persculptus* Sea")

	Suspension	Surficial Deposit	Mining	Grazing	Predatory	Other
Pelagic	9				10	
Erect						
Surficial						
Semi						
Shallow				11		
Deep			3			

3 *Chondrites*
9 *persculptus* zone graptolites
10 *Orthocones*
11 *Planolites*

In broad terms the community seen at Llangrannog represents a perturbation in the generalised consistent increase in occupation of modes of life postulated by Bambach et al (2007), in a manner similar to the disruption the End – Ordovician extinction event caused in the overall Ordovician Radiation of macrofauna (Servais et al. 2009, 2010, 2011). In its domination by a predominantly surficial fauna the guild is reminiscent of Ediacaran assemblages, although the clearly motile lifestyle of the *Diplichinites* /

Merastomichnites trace maker, and the potential presence of an agrichnial mode of life (*Gordia* & *Chondrites?*) clearly implies a greater degree of complexity.
The following figure illustrates the stratigraphic occurrence of the trace fossils present in the Llangrannog succession.

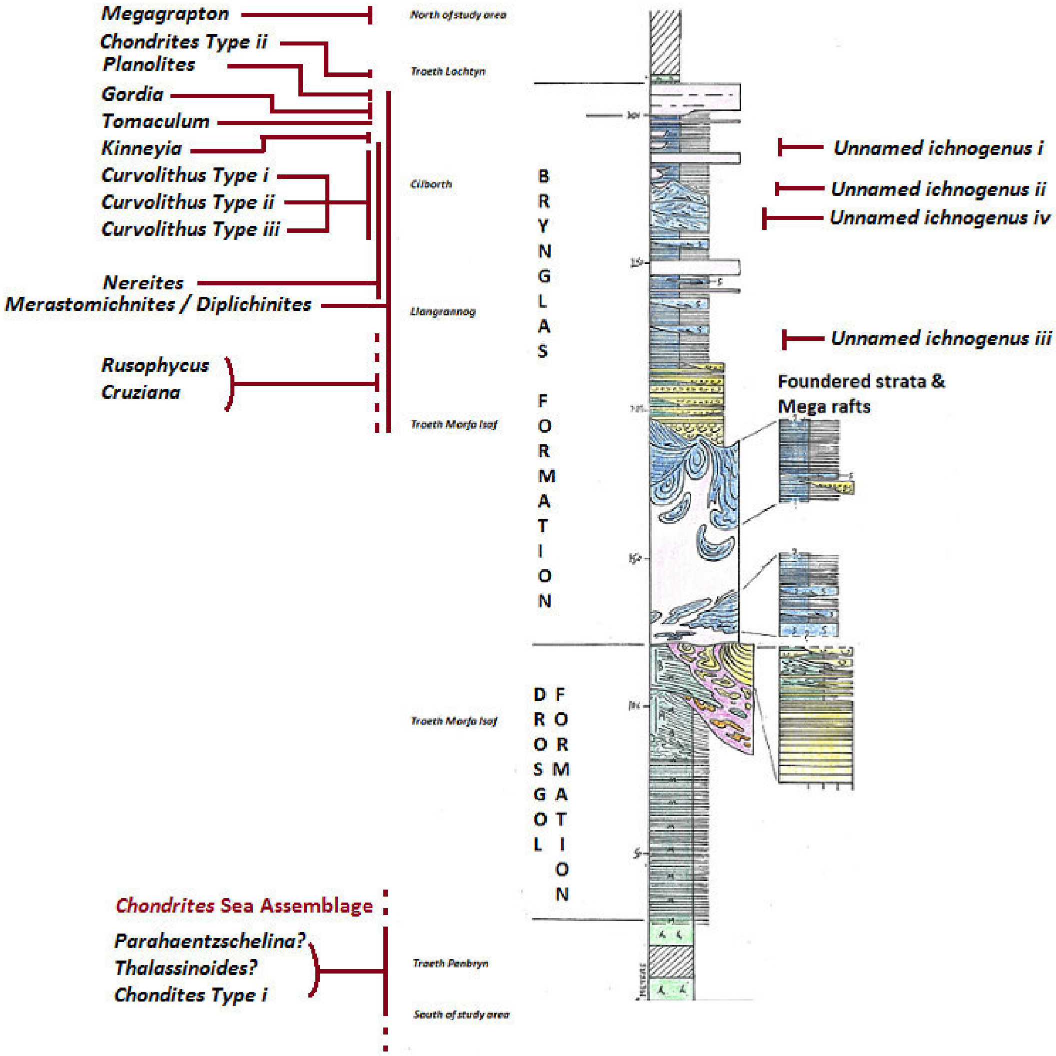


Figure 5.42 Stratigraphic occurrences of trace fossils in the Llangrannog succession *Thalassinoides* in the Brynglas Formation is not shown but occurs at a horizon just below the *Kinneyia*.

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Chapter 6:

Cwm Hirnant

"Oh, East is East, and West is West, and never the twain shall meet,
Till Earth and Sky stand presently at God's great Judgment Seat"

Mark Twain 1889

Cwm Hirnant

6.1 Context

Cwm Hirnant ("Valley of the long stream" in Welsh), is a north trending glaciated valley located south east of the town of Bala. The area is located north east of Llangrannog, but in the late Ordovician would have lain in a basin margin setting, in significantly shallower water (see Figure 3.2). This allows a comparison to be made in the sedimentological, palaeontological and ichnological record of the basin and its margin during the Hirnatian. The impact of the glacio-eustatic regression in the marginal setting is anticipated to be considerable, with substantial lateral migration of the littoral facies in response to sea level drawdown as indicated in Figure 3.4.

Cwm Hirnant is the original "type" location for the Hirnantian Stage (Bancroft 1933) and for the establishment of the eponymous "Hirnantia Fauna" as a diagnostic chronostratigraphic marker (Semple 1965). Although the global boundary markers for the base of the Hirnantian and the base of the Llandovery have been established at Wangjiawan (PRC) and Dob's Lin (Scotland) respectively, the Hirnantian Stage has been formally established as the last in the Ordovician on a global basis (Chen, Rong et al. 2006). The study area is a 2km by 2km square centred on SH 949 300 as shown in Figure 6.1 below.

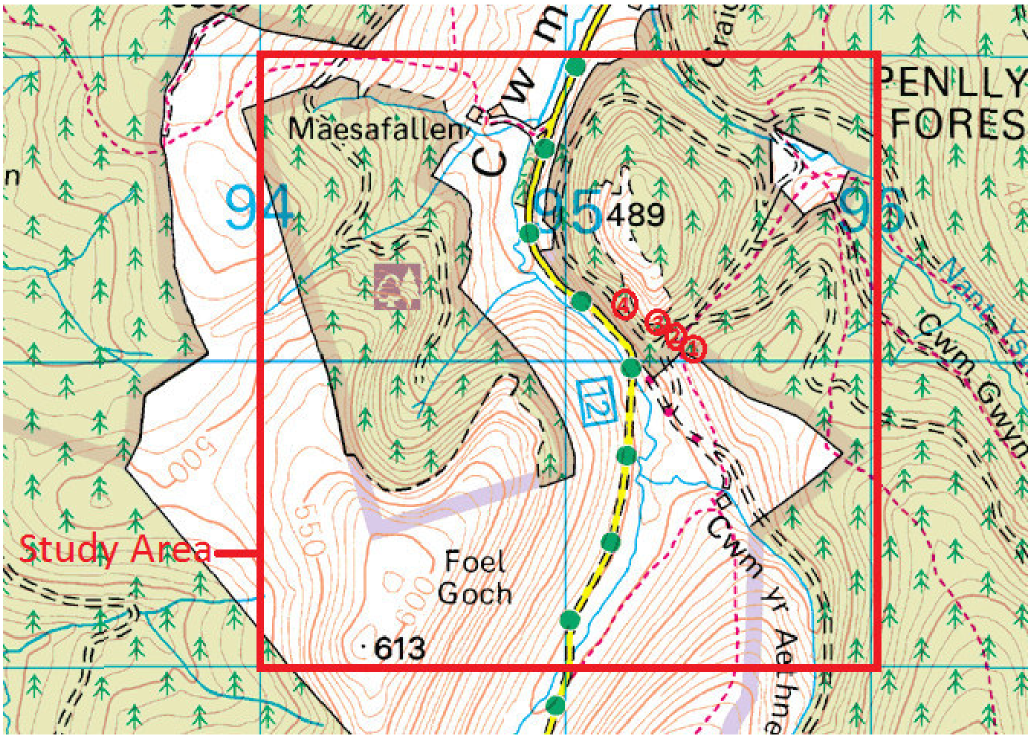

Figure 6.1 Study Area – Cwm Hirnant (base map: Streetmap.co.uk, centred at SH 949300).

The rocks in and around Bala form a background to the historical narrative of the development of stratigraphy as a fundamental tool in the geological sciences, and in particular with regard to the famous dispute between the Reverend Adam Sedgwick and Sir Roderick Impy Murchison over the nomenclature of the "*Silurian*" (s.l.) and "*Cambrian*" (s.l.) strata of the Welsh Basin (Hallam 1988). By the time of the publication of Ramsey's (1866) Memoir on North Wales. Murchison was Director-General of the Geological Survey. Murchison's position with regard to the Sedgwick-Murchison dispute was taken as the *de facto* "correct" solution giving rise to the following established 19th Century geological column:

Table No 6.1 Lower Palaeozoic Geological Column after Ramsey (1866) – bold emphasis added

Period	Series*	Lithology
Upper Silurian		Old Red Sandstone
	Ludlow Series	Tilestone and Upper Ludlow Rocks
		Aymestry Limestone
		Lower Ludlow Rocks
	Wenlock Series	Wenlock Limestone
		Woolhope Limestone and Shale
		Denbighshire sandstone, shale and slate
		Tarronen Shale
	Llandovery rocks Intermediate Series	Upper Llandovery Beds
		Lower Llandovery Beds
Lower Silurian	Caradoc or **Bala** and Llandeilo Beds	**Hirnant Limestone**
		Caradoc
		Llandeilo
		Tremadoc Slate
		Lingula beds
		Cambrian grit and slate

* Used in an informal sense **Bold** type indicates rocks broadly equivalent to Hirnantian

The Ramsey / Murchison stratigraphy as outlined above did not recognise any significant unconformity between the Caradoc and Llandovery strata, and established the boundary between the Lower Silurian (claimed by Sedgwick as part of his "Cambrian" strata) and the Upper (sometimes referred to in literature of the time as "True") Silurian rocks. Specific description is made in Ramsay (1866, p. 84), of the Hirnant Limestone specifically drawing attention to its occurrence in "*a small quarry about a third of a mile west of Cwm-y-aethnen"*.

It is stated that other than in the Hirnant Limestone itself

"*.. fossils are exceedingly scarce, and the specimens are usually very imperfect*".

The following fossils are listed as being present:

Orthis (Eostropheodonta) *hirnantensis, Orthis* (Hirnantia) *sagittifera, Orthis turgida, Orthis biforata* (and varieties), *Orthis elagantula, Orthis testudinaria, Arca edmoniformis, Modiolopsis modiolaris*

The dispute between Murchison and Sedgwick was eventually settled after their deaths, and a major stratigraphic advance made, by the tripartite division, of the lower Palaeozoic Strata into Cambrian, Ordovician and Silurian Sytems (Lapworth 1879). However this was not universally accepted by the geological community for a considerable number of years. Lapworth and his students, including Gertrude Elles, worked primarily on graptolites (Elles and Shakespear 1901), and Elles applied these techniques to a reworking of the stratigraphy of the Bala district (Elles 1922) as summarised below:

Table No 6.2 Geological Column after Elles, 1922

Period	Series	Lithology	Shelly Fauna	Graptolites
Silurian	**"Valentian"**	Cwm-yr-Aethnen Shales		*Monograptus crispus, Monograptus sedgwicki*
		Hirnant Grits and Mudstones including Hirnant Limestone	*Orthis-hirnantensis* fauna	
		Foel-y-Ddinas Mudstones	*Phacops–mucronatus* fauna	
Ordovician	**"Ashgillian"**	Moel-fryn Sandstones	Unfossiliferous	
		Rhiwlas Limestone and Mudstones	*Phillipsinella parabola* fauna	*Dicellograptus anceps* zone

Elles also drew attention to the "*old classic section*" on Pen y Dallgwm (see Fig 6.2) and its "*famous pisolitic facies of the Hirnant Limestone*".

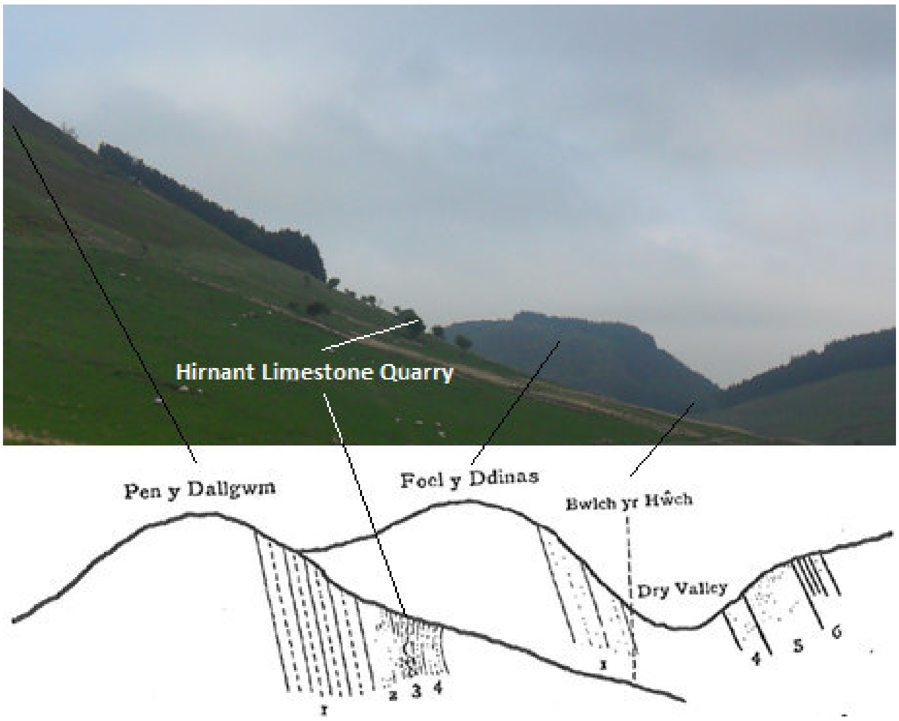

Figure 6.2 Elles' Figure 8 showing vertical / overturned? Hirnant Limestone on eastern flank of Pen y Dallgwm, Hirnant, view looking northward, the Foel y Ddinas hill presents approximately 0.75km in this sectional view.

Elles gives the following section of the Hirnant Limestone and surrounding strata.

Table No 6.3 Elles' description of Hirnant Limestone Quarry (Chwarel Cwm Hirnant SSSI)

	Thickness in feet (m)
1 Fossiliferous blue-grey mudstone , full of fossils	12 (3.66)
2 Pisolitic limestone in large concretionary masses measuring 3 X 2 feet	3 (0.91)
3 Concretionary calcareous mudstone, almost a limestone in places, and with scattered pisolitic grains; blue-grey when fresh, but weathering to a dirty cream colour	10 (3.05)
4 Dark bluish mudstone, with a few scattered pisolitic grains but few fossils	10 (3.05)

The following fossils are noted to be characteristic:

Orthis (Eostropheodonta) hirnantensis, Orthis (Hirnantia) sagittifera, Dalmanella elegantula, Strophonema siluriana, Platystrophia biforata, Monticulipora fibrosa

The total thickness in the quarry is stated to be 25 to 30 feet (i.e. 7.5-9.0m approx). Elles offers a section (her Figure 8, Fig 6.2 herein) which shows the outcrop of the Hirnant Limestone as appearing to be steeply dipping to the point of being overturned. Somewhat surprisingly Elles also records the presence at Garth Goch (SH 952 358) within the apparent "Rhiwlas Mudstone" (which supposedly underlies Elles' Moel-fryn Sandstone) of *Glyptograptus (Normalograptus) persculptus* and is one of the key stratigraphic marker taxa associated with the eponymous *"persculptus"* biozone. Elsewhere within the Welsh Basin this graptolite is associated with the recovery / transgressive phase, thought to be associated with post glacial climate amelioration.

The "*Hirnantia*" Fauna was formally established as an identifiable stratigraphically useful latest Ordovician fauna based on collections from Poland, Cumbria and "Aber Hirnant" (Temple 1965). No detailed information regarding the locations of the fossil bearing horizons in either geographic, or stratigraphic terms was given. Temple records the following constituent members of the fauna from Aber Hirnant (his Table 11) as:

Lingulella sp., *Orbiculoidea radiate, Philhedra stawyensis, Dalmanella testudinaria, Bancroftina* c.f. *bouceki, Hirnantia sagittifera, H. kielanae, Platymena polonica, Eostropheodonta hirnantensis, Plectothyrella platystrophoides.*

The stratigraphy of the Bala district was subseqently formally reviewed by Bassett et al (1966) who built on Elles' earlier work and gave the following outline of the geology:

Table 6.4 Geological Column after Bassett et al. (1966)

Series		Lithology	Lithological Description
Llandovery		Cwm yr Aethnen Mudstones	Dark blue striped mudstones
Ashgill	**Upper Bala Group u/c**	Foel y Ddinas Mudstones	Blue mudstones and calcareous siltstones, Hirnant Limestone and Calettwr Quartzite members
		---------------------------------	---
		Moelfryn Mudstones	Grey mudstones and sandstones, Rhiwlas Limestone Member
	u/c	---------------------------------	---
Caradoc	**Lower Bala Group**	Gelli-grin Calcareous Ashes	Calcareous ashy mudstone
		Allt Ddu Mudstones	Dark blue silty mudstone
		Glyn Gower Siltstones	Siltstones and fine sandstones
		Nant Hir Mudstones	Dark blue mudstones

Unconformities (denoted as u/c above) were identified at the base of the Ashgill Series associated with the Rhiwlas Limestone Member, and between the Moelfryn and Foel-y-Ddinas Mudstones within the Ashgill Series. In discussion (pg 252) Bassett et al (1966) record a number of features in the Moelfryn Mudstones and overlying Foel-y-Ddinas Mudstones, which are reminiscent of the Nantmel Mudstones, and the Drosgol and Brynglas Formations (respectively) of the Llangranog area, including:

- the general pale grey colouration
- The presence of darker *Chondrites* type burrow mottling
- The occurrence of soft sediment "penecontemporaneous" slumping (twelve such slide "Sheets" recorded at Garth Goch – the same location as Elles' record of *Normalograptus "persculptus"*).

The following fossils were recorded as being present in the Hirnant Limestone Member of the overlying Foel–y-Ddinas Mudstones:

Dalmanella (sp. 3), *Stropheodonta (Eostropheodonta) hirnantensis*, *Hirnantia sagittifera*, *Howellites* (sp. 3), *Leptaena* sp., ?*Plectatrypa*, *Dalmanitina (Mucronapsis) mucronata*

The same quarry section as described by Elles at Cwm Hirnant "*due west of Cwm-yr-Aethnen farm*" is again described, but in this instance the following section is offered:

Table No 6.5 Bassett et al description of Hirnant Limestone Quarry
(Chwarel Cwm Hirnant SSSI)

	Thickness in feet (m)
1 Unfossiliferous cleaved blue mudstone	3 (1)
2 (gap)	5 (1.75)
3 Fossiliferous cleaved blue mudstones	45 (13.7)
4 Cleaved mudstones and silty mudstones with fossils	5 (1.5)
5 Lenticular, oolithic limestone (Hirnant Limestone)	6 (1.9)
6 Silty, dark blue mudstones and siltstones	10 (3)

The implication of this published section is that there should be a total in excess of 70 feet (i.e. >21m) of strata present. There is no identified unconformity at the transition from "Upper Bala" i.e. Hirnantian to Llandovery strata.

6.2 Fieldwork

The approach taken to ground-prove the existing published mapping and stratigraphic schemes was to visit key sections and compare observation with recorded documentation. Again a 4km^2 area was selected, in this case centred around the key location at the SSSI at Chwarel Cwm Hirnant (Figure 6.1).

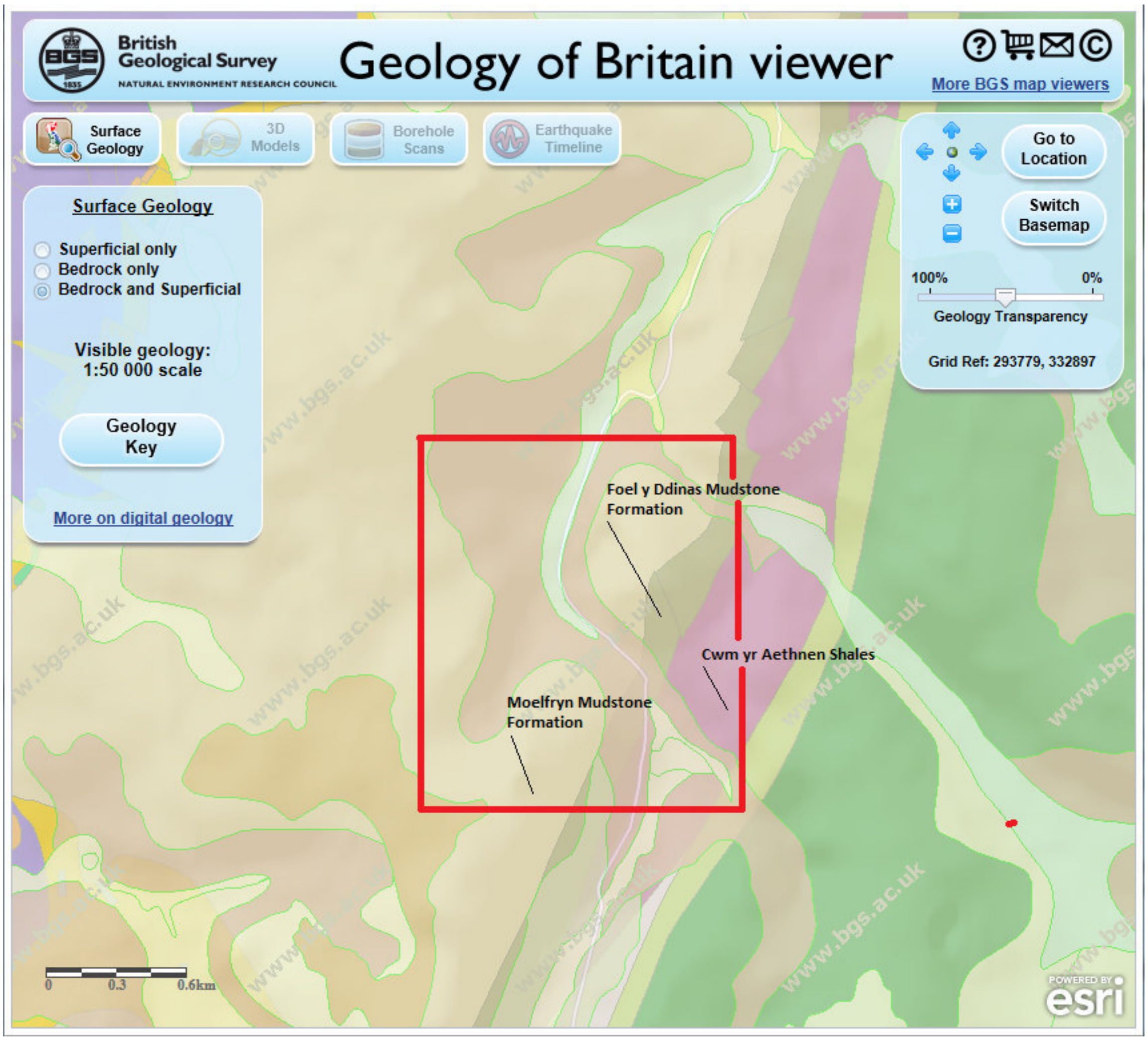

Figure 6.3 Current BGS 1:50,000 Scale Mapping of Cwm Hirnant (sheet 136) and the surrounding area as shown on the BGS Geology Viewer Web site (study area shown in red).

There are a number of fundamental problems apparent however when the two published sections are compared against each other, and against the existing site, in that:

- The two published sections are markedly different (see Fig 6.4)

- Both sections show considerably more stratigraphy than can be seen at present, but there is no evidence on the ground, nor in either of the published accounts of any trenching carried out to expose bedrock beneath the drift cover

- Whilst Elles does show in her section an apparent localised overturning of the Hirnant Limestone, she does not discuss this aspect. Bassett et al however make no reference at all to any steepening of the Hirnant Limestone, and on the contrary record the dip of the Foel y Ddinas Mudstone in the slopes above the plotted position of the Hirnant Limestone, to be 75^{o} toward the south east.

- Observations on site however indicate that the strata in the quarry dip toward the west (albeit at a relatively high angle, See Figure 6.8).

Published Descriptions					
Elles (1926)			**Bassett Whittington & Williams (1966)**		
Simplified Description	Symbolic Log	Thickness* (m)	**Simplified Description**	Symbolic Log	Thickness (m)*
			Unfossiliferous blue MUDSTONE		0.915
			gap		1.525
			Fossiliferous blue grey MUDSTONE		13.725
Fossiliferous blue-grey MUDSTONE		3.66	MUDSTONE and silty MUDSTONE with fossils		1.525
Pisolitic (Hirnant) LIMESTONE		0.915	Lenticular oolithic (Hirnant) LIMESTONE		1.83
Concretionary calcareous MUDSTONE		3.05	Silty dark blue MUDSTONE and SILTSTONE		3.05
Dark bluish MUDSTONE		3.05		**Total thickness =**	**22.57**
	Total thickness =	**10.675**			

* all thicknesses calculated from published dimension in feet X 3.05 to give m

Figure 6.4 Comparative outcrop descriptions – Cwm Hirnant

With this apparent anomaly identified it was necessary to establish the extent of the area affected by this change in the dip direction from the published local and implicit regional dip direction given that the quarry is expected to lie on the western limb of the Caledonian (Acadian) Llandderfel Syncline (Brenchley and Rawson, 2006). Fig 6.5 (below) shows the dip and dip directions identified at outcrop in the immediate area, together with two unrecorded faults present. On the basis of these observations it is apparent that the structural geology is far more complicated than previously published data would suggest.

On the basis of the relatively consistent dip direction identified up slope of the SSSI site it seems likely that the local overturning implied by Elles's section is incorrect, and that there is a parasitic fold present on the western limb of the Llandderfel Syncline, with the potential repetition of the Hirnant Limestone outcrop both up slope and downslope of the SSSI site, as indicated on Figure 6.6 (below). There is some further evidence to support this assertion as a number of pieces of the Hirnant Limestone have been recovered from talus in a lower quarry adjacent to the Vyrnwy Road.

Within the quarry itself the oolithic fossiliferous Hirnant Limestone is exposed. Whilst evidence for the "way-up" is somewhat equivocal, on balance the preponderance of fossils preserved on the bases of bedding planes (Figure 6.7) indicates a local dip to the west rather than the local over turning hypothesis.

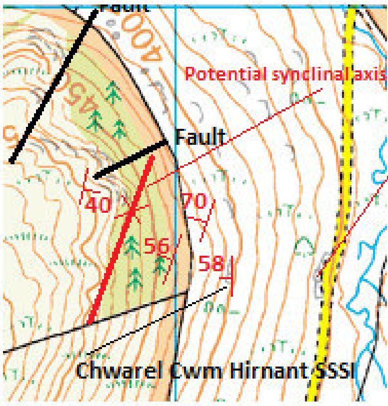

Figure 6.5: Local ground proofing showing extent of local dip variation and hitherto unrecorded faults. (Basemap Streetmap.co.uk)

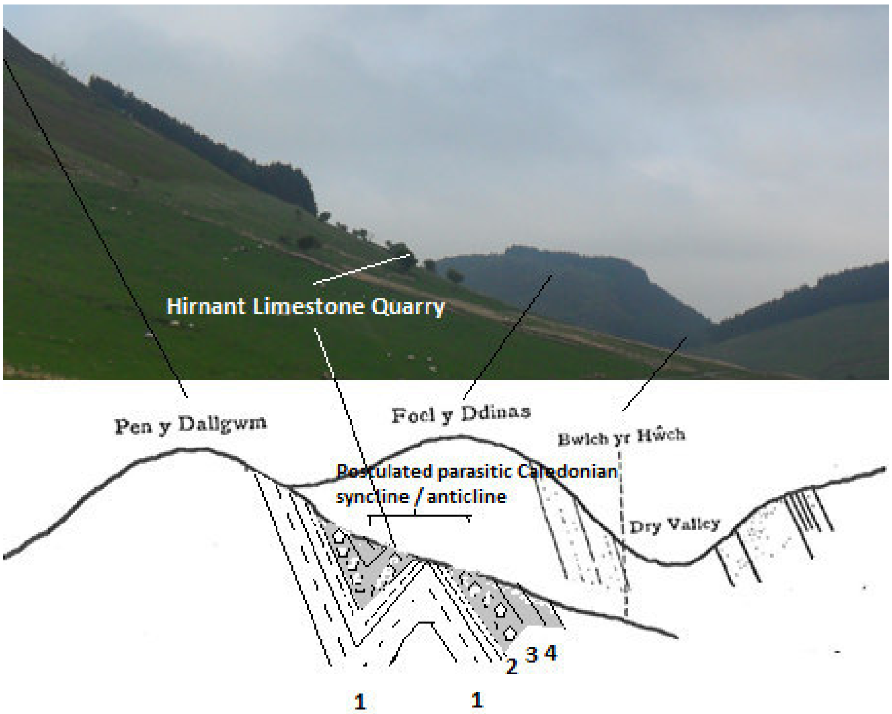

Figure 6.6: Following Elles (1922), compare with original (Figure 6.2)
1- Foel-y-Ddinas Beds, 2- Hirnant Mudstones below Hirnant Limestone, 3 – Hirnant Limestone, 4 – Hirnant Mudstones above Hirnant Limestone
(NB 1,2 and 4, all Foel y Ddinas Mudstone as defined by Bassett et al (1966).

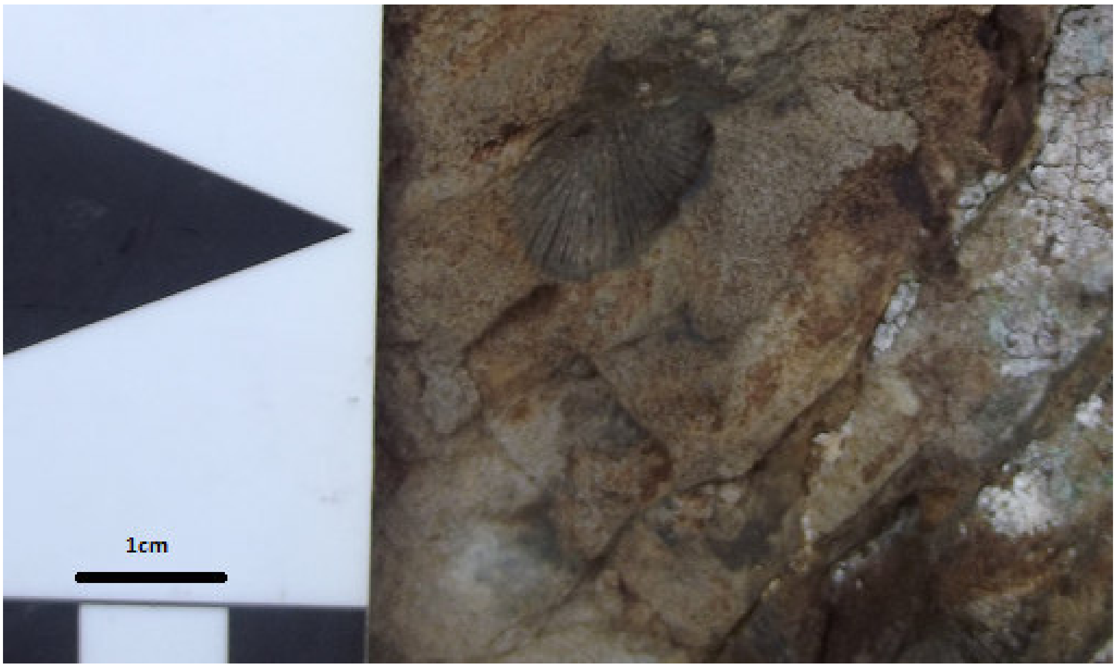

Figure 6.7: *Hirnantia sagittifera* on base of north westerly dipping bedding plane, Chwarel Cwm Hirnant

It should be noted that on lithological grounds there is no justification apparent for the mapped boundary between the Foel y Ddinas and Moelfryn Formations as shown on the published geological maps. There is good exposure in a cut forestry track running around Foel y Ddinas, and the lithology is a rather uniform grey siltstone with variable proportions of fine (sometimes micaceous) sandstone, and mudstone.

There is a distinct change into the "Hirnant Mudstone" facies in the floor of the Bwlch yr Hwch dry valley with a cherty textured thinly bedded mudstone apparent, and again with the change to a finer grained and highly cleaved slate (The Cwm-yr-Aethnen Formation), beyond. The "Hirnant Mudstone" horizon shows a number of pyritic nodules and iron staining of indeterminate, put possibly organic origin (detailed textural characteristics of any fossils have been destroyed by weathering / oxidation of the sulphides).

6.4 Palaeontology and ichnology

Formal palaeontological descriptions of the fossils encountered within the sequence is outside the scope of this study. In contradiction to the situation in the Llangrannog area however, the macrofauna present in the Cwm Hirnant sequence is plentiful. A substantial "*Hirnantia*" fauna has been collected with a number of reasonably well preserved brachiopods including the eponymous pairing of *Hirnantia sagittifera* and *Eostropheodonta hirnantensis*. It should be noted that whilst the quality of preservation of the fossil material within the rock is not particularly good, the quantity of material preserved locally within the Hirnant Limestone is suggestive of a Concentration Lagerstatte. A number of fossils have been collected throughout the course of this study (see Appendix 1) and will be offered to appropriate University or Museum Collections for further study, by others in due course.

The situation with respect to the body fossils in comparison between Cwm Hirnant and Llangrannog is clear, in that whilst body fossils are absent at Llangrannog in the Brynglas Formation, and reasonably plentiful in the coeval Hirnant Limestone Member. With respect to the trace fossils the situation appears reversed. The ichnocoenose at Cwm Hirnant is depauperate in comparison. There are apparent biofilms present in the Moelfryn Mudstone Formation, and *Megagrapton* type traces are common on turbidite bases in the overlying Cwm yr Aethnen Formation. The "shoaling" that is generally associated with the generation of ooliths is of itself a process of reworking of the sea bed, and as such any Tier 0 and Tier 1 traces that are left by epibenthic fauna will be destroyed by the primary sedimentary processes.

Chondrites was seen in the underlying Foel y Ddinas Formation (believed to be at least in part equivalent therefore to the Nantmel Mudstone Formation) at Bwlch y Groes (SH914231) approximately 8km south west of Cwm Hirnant.

Despite significant hours searching in the vicinity of the contact between Foel y Ddinas Formation and Cwm yr Aethnen Formation no evidence of the Chondrites bearing "Mottled Mudstone Member" has been seen. The absence of this horizon would be consistent with the presence of an unconformity at this horizon.

The location of Cwm Hirnant in the east of the basin suggests that at the peak of the glacial lowstand, the area was emergent, or at least subject to mass wasting of sediments. Consequently, despite the presence of marine or estuarine shallows with a reasonably well established *Hirnantia* Fauna conditions were unsuitable for the preservation of any significant number of surface traces associated with any of the more motile animals present, but fossilisation was generally associated with transported and sorted animal fragments, favouring preservation of tough faunal elements such as brachiopod shells.

This is supported by the apparent absence of a significant carbon isotope excursion at Cwm Hirnant (Vanderbroucke, pers. com., 2015). Brenchley and Rawson (2006) note the following with respect to the Calettwr Quartzite, (which Bassett et al (1966) take as a lateral equivalent of the Hirnant Limestone):

"*..the Calettwr Quartzite occupies a position near the top of the Foel-y-Ddinas Mudstones Formation and overlies a large non-sequence. Much of the earlier part of this Hirnantian formation seems to have been removed during the marine low stand, suggesting that a bathymetric high here suffered erosion and possibly local emergence..*"

Mucronapsis mucronata has been recorded in the Hirnant Limestone Member (Bassett et al 1966) and from the Foel y Ddinas formation (Elles 1922) this distinctive trilobite has not been found during my field work. A single possible specimen of a small "cruzianid" burrow was found to the south west near Llanymawddwy (Specimen No KHN0051).

6.5 Microscopy

During research with respect to the ichnological and palaeontological collections at the Sedgwick Museum a number of thin sections of the Hirnant Limestone from the Hirnant Quarry prepared during a previous uncompleted PhD study were discovered (Magor, pers com, 2012). These were examined using a digital optical microscope (courtesy of Fugro CGG) and are shown and described in detail in Appendix 4. Of particular interest is the occurrence of a single reasonably well preserved conodont element (image **g),** as well as other organic material tentatively assigned to fragmentary sponges or calcareous alga.

The lithological characteristics of the Hirnant Limestone are reasonably consistent, seen to comprise a very fine grained matrix formed from a few tens of micron diameter grains, with well rounded but typically elliptical rather than spherical ooids of 500 micron to a maximum of 2mm diameter. The ooids are generally found in a matrix supported condition. The ooids themselves are seen to have been formed by precipitation onto a range of pre-existing elements including seed grains, lithic clasts and in one case an apparent discrete pyrite framboid.

Brenchley and Newall (1979) associate Hirnantian oolithic limestones in the Oslo region with the presence of strong tidal currents on a shallow marine (shelf) associated with the peak regressive phase and links this with the establishment of "*coquinoid accumulations on carbonate mudmounds"* which can be considered analogous to the concentration lagerstatte type of fossilization apparent in the Hirnant Limestone.

Figure 6.8 shows a close up view of a loose hand specimen recovered from the lower Vyrnwy road quarry. In hand specimen the fine grained matrix supported nature of the lithology is not apparent, and the rock appears as an oolithic grainstone.

Figure 6.8: Close up image of Hirnant Limestone showing mm scale ooids (generally seen as voids where grains have been removed) together with brachiopod shell fragments, and a complete internal mould of *Hirnantia sagittifera*

6.6 Karst Weathering of the Hirnant Limestone

The result of the widespread deposition of extensive shelf carbonate is important. The implication of the significant Hirnantian eustatic drawdown of sea level is to expose that shelf succession to potential weathering in the sub-aerial environment. Weathering of carbonate successions produces the well-known "karst" type environment, and there is widespread published data indicating the presence of karstic weathering of Ordovician carbonate sequences throughout the world (Kump, Arthur et al. 1999; Calner, Lehnert et al. 2010; Keller and Lehnert 2010; Lehnert, Mannik et al. 2016). The eponymous "Hirnant Limestone Member" is distinctly oolithic in nature (see Figure 6.8), and is locally highly fossiliferous, but with a restricted diversity brachiopod macrofauna (see Specimens KHN0014, KHN0018, KHN0038 and KHN0066). Observations made at Hirnant have confirmed the presence of karstic features both in-situ, and in loose quarried blocks in the vicinity of the Chwarel Cwm Hirnant SSSI (Figures 6.9 and 6.10). Similar karstic features were seen in rocks of the same age at both Meifod, Powys, and considerably further afield in Keisley, Cumbria, and at Oslofjord.

The implications of the shoaling conditions in the littoral facies and the karstic weathering in the adjacent aeolian and sub-littoral environments, are that shallow tier traces are unlikely to survive shoaling, and even if they were they would be highly likely to be eroded, or disturbed prior to the onset of diagenesis. In comparison with the Llangrannog area then, the Hirnantian of the Cwm Hirnant does not offer the same potential for preservation of trace fossils.

Figure 6.9: Karst weathering surface visible at the top (right hand side) of in-situ north westerly dipping Hirnant Limestone (Scale bar = 150mm)

Figure 6.10: Karstic weathering surfaces on a loose boulder of Hirnant Limestone (adjacent to Hirnant Lower Quarry).

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Chapter 7:

The Geoconservation Perspective

Trace fossils have great potential for increasing our understanding of these important events in the evolution of life on earth: we have only just begun to scratch the surface

RJ Twitchett and CJ Barras (2004)

Love Nature? Learn science and speak logic.
Gregg Easterbrook (1998)

Between the living and inert matter of the biosphere, there is a single, continuous material and energetic connection
Vladimir Vernadsky (1931)

The Geoconservation Perspective

7.1 Historical status

The rocks of the Welsh Basin have formed part of the narrative of historical geology. By simply referring to the current geological column (Figure 7.2) and Geological Map of Wales (Figure 7.3) we can see the presence of place names at Period, Stage and Series level that pay homage to Welsh geography.

Standard stratigraphic nomenclature records "Cambrian", "Ordovician" and "Silurian" at Period level (*Cambria* being the Latin term for Wales and parts of Western England, the Ordovices and Silures were Iron Age Celtic tribes established in Wales and the border country). Elsewhere Series and Stage names reflect Welsh place names like Llandovery, and Tremadoc and the rivers Hirnant and Aeron; Ludlow and Wenlock represent the English Borderlands.

The Global Boundary Stratotype Section and Point (GSSP) at the base of the Hirnantian has been established in Hubei Province, China (Chen, Rong et al. 2006). Similarly, the two stages beneath the Hirnantian have been named as the Katian and Sandbian (Bergström, Finney et al. 2006). The defined GSSP for the base of the Silurian (and effectively therefore, the top of the Hirnantian) is located at Dobb's Lin, near Moffat, Scotland (Rong, Melchin et al. 2008), Figure 7.1).

Figure 7.1: The GSSP for the base of the Silurian at 443.4Ma, Dobb's Lin, Scotland. The shaft of the hammer is located along the chronostratigraphic boundary with rocks to the right of the picture being of latest Ordovician age, rocks to the left earliest Silurian.

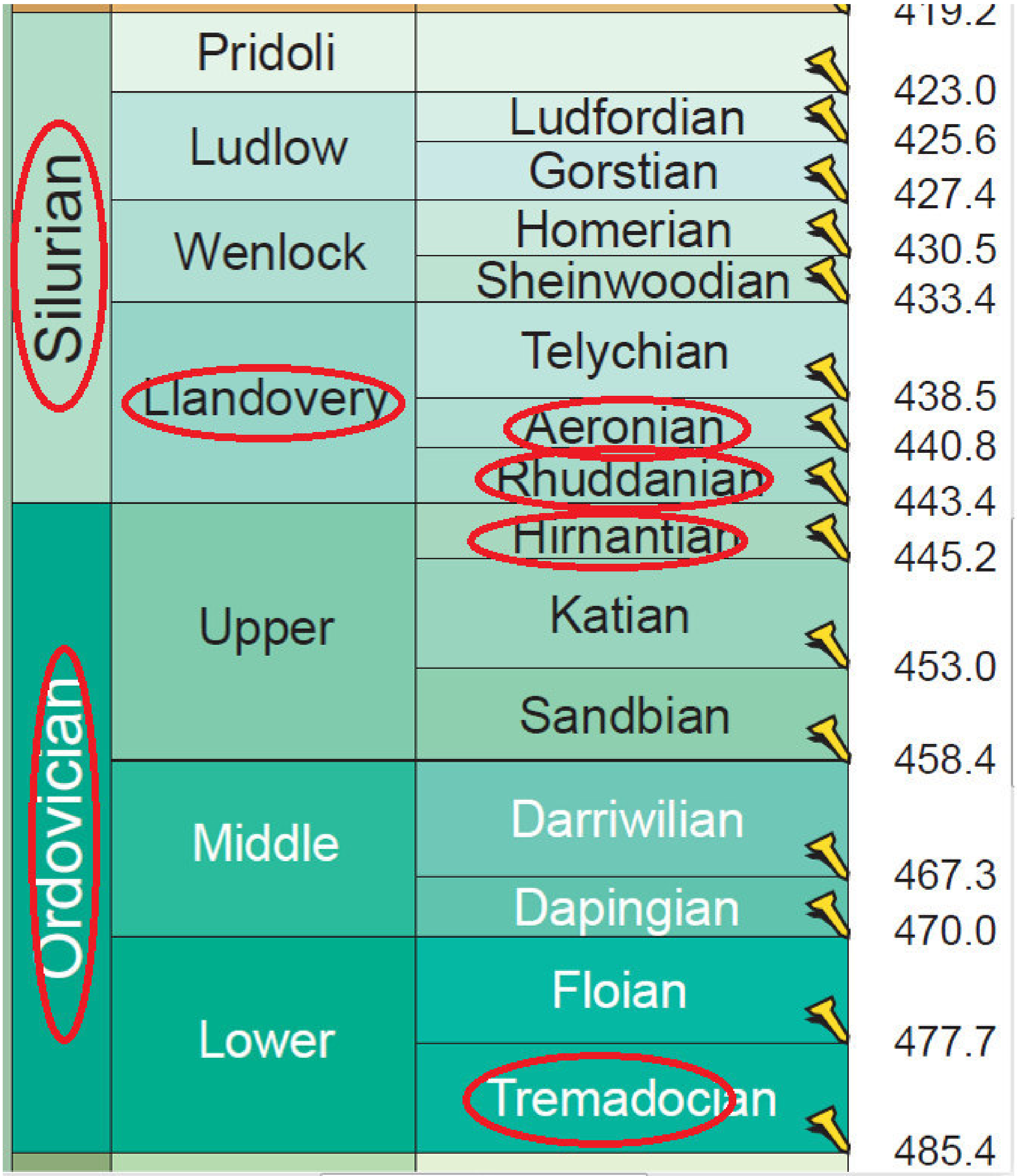


Figure 7.2: Current stratigraphic framework for the lower Palaeozoic showing chronostratigraphic correlation (right hand column) and the location of fully defined global stratigraphic points. The Hirnantian Stage is represented by a 1.8 million year interval between defined GSSPs in China and Scotland. Elements nmed after Welsh locations or ancient native Welsh tribes are ringed in red.
Data from current published Stratigraphic Chart (Cohen, Finney et al. 2013)

The origin of the term "*Hirnantian*" used almost ubiquitously as the globally recognised final stage of the Ordovician System follows the early postumously published, palaeontological studies by Bancroft (1933) and is inextricably linked to the establishment of the widely recognised *Hirnantia* Fauna (Temple 1965) with its two eponymous brachiopod constituents *Hirnantia sagittifera* and *Eostropheodonta hirnantensis*.

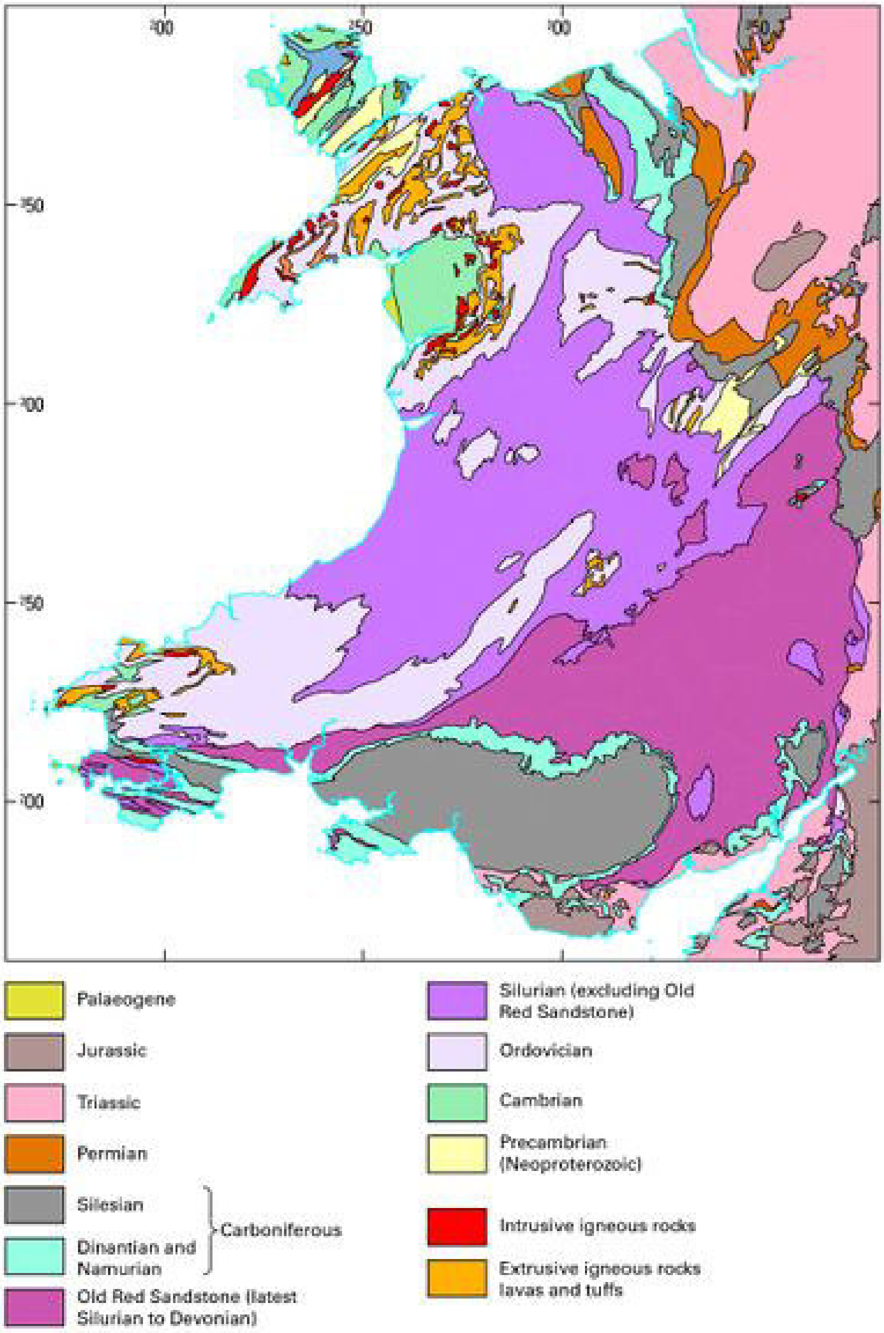


Figure 7.3: Current Geological Map of Wales (from Howells, 2007). The Ordovician / Silurian boundary is represented by the demarcation between the two purple and shades (Ordovician the paler of the two).

The trace fossil assemblage described from the Llangrannog area is an extremely rare, possibly unique (in Wales certainly, but potentially globally), example of well preserved, typically epichnial traces representing a community of soft bodied, opportunistic taxa occupying ecospace normally occupied by much more widely known species with hard body parts. The particular conditions that allowed development of the taphonomic window remain obscure, but are associated with the sedimentology of the glacial lowstand and sequence boundary, and with the ecological pressures on any deep burrowing fauna.

7.2 Geological influence of work in the Welsh Basin.

Early workers in the area were at the forefront of the establishment of basic geological and stratigraphic working methods. The dispute between Darwin's early career mentor the Reverend Adam Sedgwick (1785-1873), and Sir Roderick Impy Murchison (1792-1871) Director of the Geological Survey, over the status of the Cambrian / Silurian "Bala" Series and associated rocks, is very much part of the lexicon of Historical Geology (Hallam 1988). In the early years of the 20th Century Charles Lapworth (1842-1920), having carried out his benchmark work in the Southern Uplands of Scotland extended his considerable advances into the Welsh Basin and was responsible for establishing the tri-partite split of the lower Palaeozoic into Cambrian, Ordovician and Silurian Periods. He also named the Ordovician, as a Series separate from the older Cambrian, and younger Silurian (Lapworth 1879) resolving the earlier Sedgwick / Murchison dispute. Lapworth's research students Gertrude Elles (1872-1960) and Ethel Wood (1871-1946) made further considerable advances in their graptolite work in this area, culminating in the publication of their monograph on British graptolites (Elles and Wood 1918).

The concepts that grew out of the "geosyncline" paradigm were very much a consequence of work undertaken in the Welsh Basin, with the seminal paper on this subject (Jones 1938) drawing heavily on a field work programme based around Llandovery. Subsequent workers (Cocks and Fortey 1982) used the macro-faunal fossil record of these rocks, amongst others, to confirm the inferences of the theory of plate tectonics, tracking faunal migration, extinction episodes and the like, and identifying the closure of the Iapetus Ocean in the run up to the Caledonian (Europe) and Appalacian (North America) orogens.

These rocks continue to provide additional new finds of global significance to the wider palaeontological community, with recent publications derived from the Welsh Basin and Welsh Borderland recording important evidence relating to colonisation of the terrestrial ecosystems by land plants (Morris, Wright et al. 2012), phylogeny of molluscs (Sutton, Briggs et al. 2012), soft body fauna (Botting 2004; Botting, Muir et al. 2012), and micropalaeontology (Vandenbroucke, Hennissen et al. 2008).

7.3 The question of value

Whilst road, railway and quarry sections have proven hugely beneficial to the geological sciences in providing insight into the rock strata beneath the superficial veneer, it is apparent that there are significant risks associated with the “Anthropocene” and specifically our propensity to move rock and superficial materials, and to engineer our landscape to suit our needs. Important geological features can all too easily be lost, beneath a refuse filled quarry, behind a surface “protection” layer of concrete or wire mesh, beneath a spread of engineered fill, or (perhaps as a worst case example) crushed, broken and turned into aggregate.

If it is reasonable to assume that important geological features have some “value” then clearly their loss is something that, if it can be avoided, should be. The question of exactly how we can assign a value to the physical geological object is a difficult one however. To those without formal geological education it may be the case that one rock looks much like another. Rocks which contain interesting minerals or obvious macro fossils do generally arouse some initial interest from casual observers, but that interest is sometimes fleeting.

It is the case that “size is important” in this context. Few children are unmoved by the geological concepts of dinosaurs / ichthyosaurs / mammoths / sabre toothed tigers having walked, or swum through their neighbourhood in times past. However, detailed stratigraphy is increasingly dependent on microfaunal or microfloral content, and geochemical markers, and it is only modern research technology that has revealed the important role that acritarchs, conodonts, chitinozoa, detrital zircons and carbon isotope excursions have in stratigraphy. It is surely easy to understand that the general public may not be enthused by thick sequences of seemingly monotonous mudstones, shales and sandstones when none other than Murchison had apparently referred to similar rocks in Germany (without detailed knowledge of their micropalaeontology or geochemistry) as “*these interminable grauwackes*” (Geike 1875).

The concept of value has been widely discussed in relation to biological diversity (biodiversity). Jeffries (2006) identified:

- “Use Value” – comprising direct uses such as harvesting and tourism; indirect use such as ecosystem function; and future use (described as insurance against the unknown).

- “Non-use Value – the benefit gained from NOT over exploiting an element of extant biodiversity, i.e. what we are willing to forego to ensure that the species can be considered a bequest to future generations.

With respect to geoconservation purposes, values have been classified into the following six categories (Gray 2005):

- Intrinsic Value (the value associated with a feature's worth in and of itself, rather than in its being used by us)

- Cultural Value (at its most extreme the sense of being part of a whole as implied by the native American or aboriginal Australian ideology)

- Aesthetic Value (the value attributed to a feature by its interaction with our senses – usually in the context of the perception of beauty in a natural landscape)

- Economic Value (in a world fuelled by fossil fuels, and with economies underpinned by the price of gold – this is the most obvious valuation ascribed to our geological environment)

- Functional Value (relates to the work done by elements of abiotic nature in for example – acting as sinks for greenhouse gases, for filtering and thereby cleaning groundwater etc.)

- Scientific Value (broadly equivalent to "geotopes" as defined by some in the geoconservation movement).

It is of concern perhaps that the Scientific Value, so defined, comes last in the listing. As a category Gray (2005) further sub-divides this into four further sub-classes:

- Geoscience research (History of Earth, evolution, geoprocesses)

- History of research (Early identification of unconformities etc.)

- Environmental Monitoring (Climate change, sea level change, pollution)

- Education & Training (Field studies, professional training)

Valuation in respect of the need for geoconservation therefore needs to reflect a value to society in the rock that may be (depending on that valuation) greater than the economic value of the rock material itself, i.e. that value that would be assigned by a mineral surveyor to a mineral owner for example, when it is considered as a potential source of aggregate (or mineral); as a foundation for a newly built road; or as a receptacle for domestic refuse (the latter two examples being examples of "functional value"). Perhaps the most obvious example of where the Scientific and Aesthetic Values of a geological material exceed that of the economic valuation arises from the prospect of using a slab of Solnhofen Limestone, such as that shown in Figure 7.4 as a lithographic material along with the other products of that particular quarrying operation.

With respect to the Scientific Value sub-classes, as defined above, it should be noted that both "History of research" and "Education and Training" are to a large extent backward looking and reflect a historical value which is based on known outcrops, recorded work, and the current state of geological knowledge. The two sub-classes "Geoscience research" and "Environmental Monitoring" are forward looking, involving exploration of the unknown. For the purposes of this research I propose the term "Geovalue" to reflect this somewhat abstract concept and note that in ascribing a value to this aspect it is necessary to consider a future Geovalue which reflects the loss to society, associated with a geological items' permanent destruction, or its permanent sterilisation. It should be noted that this concept of "Geovalue" (*sensu* Nicholls) as defined here, is different to the concept of Geovalue (*sensu* Scott) which relates to "Valuing Geodiversity for Conservation" (Scott 2005), is therefore much broader in application, and relates to all six of Murray's sub-units.

Figure 7.4: Solnhofen Limestone from Saxony, Germany – with a specimen of *Archaeopteryx* (image used with permission from National Museum of Wales)

Resource geologists utilise the "McKelvey" and "Modified McElvey" boxes (McElvey 1972) to classify the concepts of resource and reserves and this can be extended and applied to aid visualisation of some key concepts relating to geoconservation as shown below:

Table 7.1: The Original McKelvey Classification Scheme

	Discovered	Undiscovered
Commercial	Reserves	Resources
Sub-commercial	Resources	Resources

Table 7.2: Modified McKelvey Classification Scheme

	Discovered	Undiscovered
Commercial	Reserves	Prospective Resources
Sub-commercial	Contingent Resources	

The McKelvey scheme is a broad simplifying scheme that instantly allows visualisation of the economic value of the particular commodity that is being considered. For a "prospective resource" to become a "reserve" it is necessary for the prospect to be proven. For a "contingent resource" to become a reserve, in addition to being proven, the economic constraints need to be removed, either by an increase in the value of the commodity, or by technological innovation allowing it to be worked at less cost.

The following table illustrates the conceptual use of a modified McKelvey Box in respect of Geoconservation, with the axes modified to represent the state of knowledge relating to a particular location, and the potential Geoconservation value ascribed to it.

Table 7.3: McKelvey Classification Scheme for Geoconservation

	Known and Recorded	Unknown or Unrecorded
Highly Valued	Contingent Protection	Unprotected
Under Valued	Unprotected	

Consideration of the above table makes it obvious that an undervalued element of our geodiversity is offered no particular protection, and that is to be expected. What is of more concern however is the fact that this box illustrates that even a highly valued object, if it is unknown (or unrecorded) can be offered no protection. In order for a location (site or feature) that is currently unprotected to gain protection it must be discovered and be recorded, and it must be deemed to be of sufficient value. The descriptor "*Contingent Protection*" implies that even in the event that a site is known or recorded, and deemed to be of high Geoconservation Value that protection remains contingent upon the economic value associated with working or removal of a site not exceeding the perceived value associated with its protection or retention.

Current geoconservation efforts relate almost exclusively to discovered and therefore already valued elements of our geodiversity, and can be divided into two categories: formal, and informal, with the formal grouping further sub-divided into Statutory and non-Statutory undertakings. The Statutory undertakings in Wales are devolved matters and lie with the Welsh Assembly Government (WAG), and are administered by Natural Resources Wales (NRW). It should be noted however that should UK national policies (such as Energy Supply & Demand) conflict with WAG policy the UK National Policy may dictate over WAG decision making. The statutory tools used by NRW are the establishment of Sites of Special Scientific Interest (SSSI), supported by the Geoconservation Review (GCR) (Ellis 2011). The concept of the SSSI was introduced into UK legislation with the enactment of the National Parks and Access to the Countryside Act, 1949; and was developed further with the Wildlife and Countryside Act, 1981. As stated previously these matters in Wales were devolved to the Welsh Assembly by the Government of Wales Act, 2006.

Figure 7.5 (below) shows the relationship between the set of statutorily protected SSSI sites in the UK which are derived from the set of GCR sites and the informal Regionally Important Geodiversity Sites (RIGS) designation sites (which are a material factor under the Planning Regime). As the GCR system matures it is anticipated that some designated RIGS sites will become future GCR / SSSI sites.

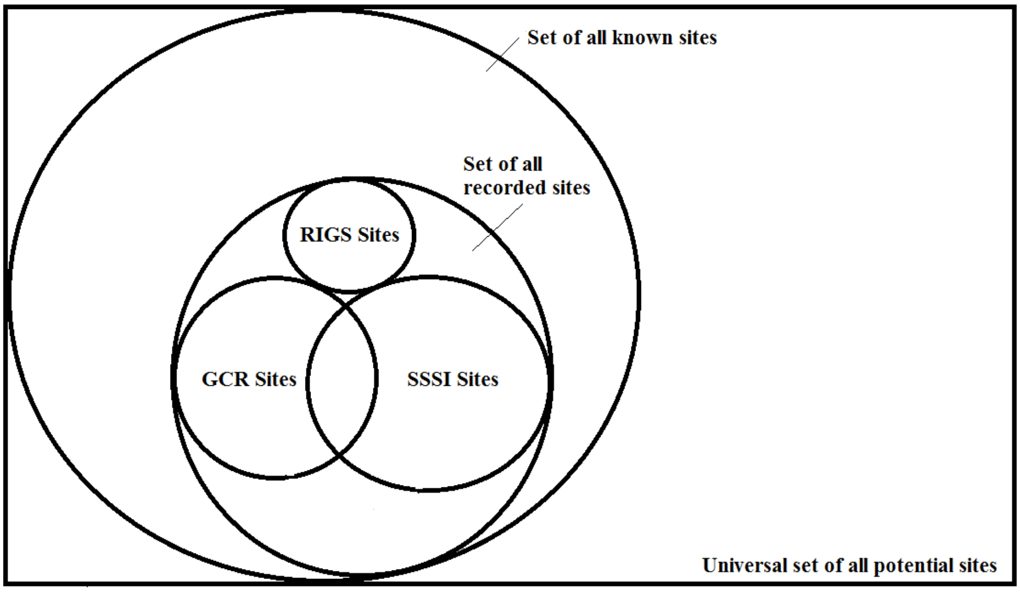


Figure 7.5: Venn Diagram illustrating the relationship between the various levels of protection and state of knowledge with regard to geological sites. The majority of sites lie outside the "known sites" category reflecting the fact that geological knowledge is necessarily limited to available exposure.

To be considered for GCR status a site needs to satisfy three criteria:

1. It needs to be of important on an international basis to the community of Earth Scientists

2. It must contain exceptional features, and /or

3. It should be representative of a defined Earth Science feature, event or process.

Of these criteria it should be immediately evident that features of geological interest are entirely unprotected whilst they remain undiscovered or unknown.

RIGS sites can be assigned by a broader series of criteria, these being:

1. Educational
2. Scientific
3. Historical
4. Aesthetic

It is therefore apparent that many sites considered for designation as RIGS sites will not be suitable for subsequent consideration under the GCR / SSSI schemes.

In order for sites to be designated as RIGS, GCR or SSSI it is stressed that there must be an existing body of knowledge relating to that particular site. All such designations are therefore backward looking, reflecting what is known. There is no formal requirement to consider the geological potential of a site under the planning regime in the same way that is required, for example, in respect of sites with potential archaeological or biological interest. The difference between the treatment of geological and archaeological heritage under current legislation has been remarked on by others (Prosser, Bridgland et al. 2011).

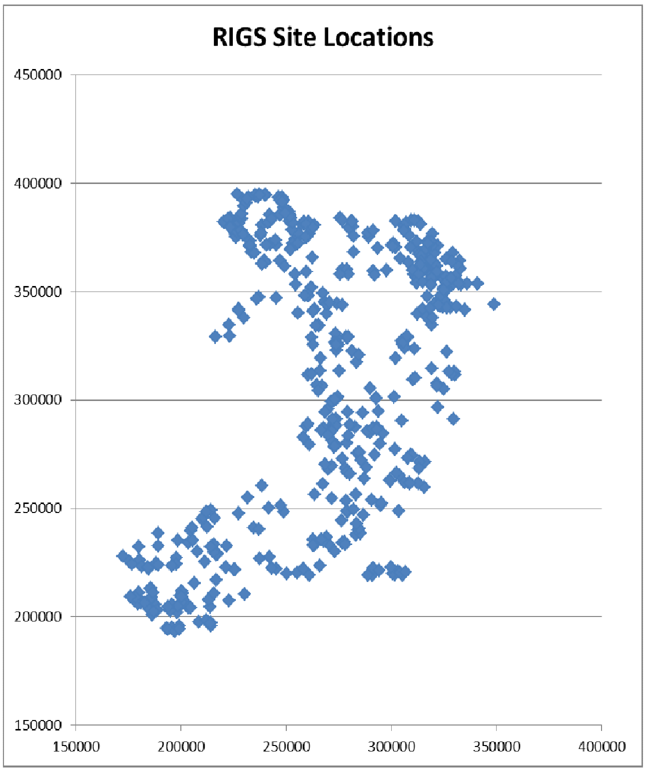
Monro's comment (2011):

> "*The rich diversity of the British geosystem is a powerful resource and encouraging active engagement together with sustainable conservation might just help to create a Society which is more aware of the geosphere that sustains us all.*"..

could easily have been written with the geology of the Welsh Basin and the adjacent borderland countryside in mind.

The informal protection is that which arises as a consequence of a site being indirectly associated with some other element of the environment that is offered protection. In this manner an element of geological conservation rides "piggy back" along with a highly valued element of landscape, flora, fauna or heritage. An important point to note is the fact that many outcrops with potential significant future Geovalue are afforded some level of protection due to the coincidence of their placement within an otherwise statutorily protected location (SSSIs protecting the Berwyn Mountains and Wye Valley protect significant Hirnantian outcrop). Similar fortuitous protection can arise by a site's location within, for example, a National Park or designated Area of Outstanding Natural Beauty.

Figure 7.6 shows a plot of the co-ordinates of the existing RIGS site in Wales (data supplied by Natural Resources Wales (Roberts 2013)). The quite obvious apparent absence of sites in the south east corner of the Principality reflects a failure of the British Geological Survey to pass on the records of their work in this part of the area to NRW. The relatively high concentrations of RIGS sites in Ynys Môn / Anglesey and in North East Wales reflect a system bias associated with respectively the work of the Môn Geopark, and the Gwynedd and Môn RIGS group in the North West; and the NEWRIGS group in the North East. Burek (2008) has detailed reasons for the particular activity of these regional groups.



A significant void in the RIGS sites is apparent in and around the locale of Corwen, Bala, Dolgellau etc. in mid North Wales. This can only reflect a lack of attention to this area, as these areas hold some of the most important outcrops in relation to historical geology in the world – including the "Type" area of the Hirnantian itself at Cwm Hirnant, near Bala (Bancroft 1933).

Figure 7.6: Locations of existing recorded RIGS sites in Wales

Whilst geoconservation (and the broader concept of geodiversity) is a relatively new formal discipline in Earth Science departments (see Figure 7.8), the broad philosophy that it carries with it are based on some of the oldest philosophical and religious traditions. The Qu'ran (Koran) instils the concept of "*khalifah*" (stewardship); Buddhists are taught that "*compassion*" should include care for the environment, and despite the sometimes excessive reference to "*dominion over….*" in Judeo-Christian scripture, there are plenty of alternative references to stewardship, care for the environment, and respect for the natural world in Western Scripture.

Perhaps the most extreme versions of this sort of philosophy are seen in the animist or totemist cultures of, for examples, the aboriginal peoples of Australia, and North America:

Please take me back my Mother the Land
Embrace me like Mother and Child
The message goes out from your children who shout
Only visitors and there for a while

With the onset of the industrial revolution early mining law and practice evolved in a manner designed seemingly to minimise, or at least recognize adverse environmental impact.

*"But besides this, the strongest argument of the detractors is that the fields are devastated by mining operations, for which reason formerly Italians were warned by law that no one should dig the earth for metals and so injure their very fertile fields, their vineyards, and their olive groves" (*Agricola 1556)

Mining law developed primarily however due to problems in common law disputes arising from mining practice, such as that described in Wirksworth, Derbyshire in 1673 between "dried up" water mill owners and mine sough (drainage) tunnellers (Slack 2000).

However, with the onset of industrial scale extraction practices, (associated with the influence of imperialist politics, a utilitarian perspective, and the nineteenth and early twentieth century focus on production, growth and economy) environmental stewardship lagged behind industrial activity. In the 1960s, 70s & 80s, environmental awareness in general, grew alongside other "*left leaning*" philosophies (feminism, pacifism, disarmament, etc.). However, explicit concern for the natural environment has until recently been dominated by concern for elements of the biosphere, i.e. the animals, plants and other elements of biotic nature that we share our planet with. Concern for "*abiotic nature*" (that is the elements of the lithosphere that underpin all the diverse biota) has been generally overlooked. However, with even a cursory examination of some historical manuscripts it is evident that current concerns for the preservation of abiotic nature hark back to concerns expressed many times, by many writers, over many years. Some examples follow, some explicit, some rather more subtle, but all confirming that concern for our apparent profligacy with respect to broad geodiversity is not new:

> *"Yet for half a century and more I had been crying havoc and chanting Milton's dirge: 'Farewell happy fields where joy for ever dwells, hail horrors', as though we were already doomed to become a race of mechanised men in a macadamized desert.."*(Williams-Ellis 1971)

> "*This part between the Camel and the Eagle, that you know and love as much as I do, is and should continue to be pure geology forever, without anything that can cause damage to it: I do state it. It is a mythological place made for the Gods more than for men and it should continue as is*" (Dali 1961).

> *"What will be the future of this 30 miles of coastline, so richly endowed as a training ground and museum of geology? Few tracts of equal size could raise so*

many claims scientific, aesthetic and literary, for preservation as a national park. At present however, it seems that little can be done to save it from falling piecemeal before the builder. ………If the English of the present generation allow this heritage of the community to be irreparably spoilt for private gain they will be held by posterity to have been unworthy to possess it. To all geologists who have enjoyed and profited by this coast, an appeal is made to do their utmost to preserve it"(Arkel 1947)

Man must be made conscious of his origin as a child of Nature. Brought into right relationship with the wilderness he would see that he was not a separate entity endowed with a divine right to subdue his fellow creatures and destroy the common heritage, but rather an integral part of a harmonious whole. He would see that his appropriation of earth's resources beyond his personal needs would only bring imbalance and beget ultimate loss and poverty for all (Wolfe 1945).

Life is, thus, potently and continuously disturbing the chemical inertia on the surface of our planet. It creates the colors and forms of nature, the associations of animals and plants, and the creative labor of civilized humanity. And also becomes a part of the diverse chemical processes of the Earth's crust. There is no substantial chemical equilibrium on the crust in which the influence of life is not evident, and in which chemistry does not display life's work (Vernadsky 1926)

7.4 The question of future scientific value

This question is closely related to Jeffries (2006) concept of "insurance against the unknown" for biodiversity. It is something of a truism in dealing with aspects of geological heritage that once gone, something is lost forever; it can be considered "extinct". As our conceptions of value change over the years it is often the case that society finds itself revisiting the discarded waste of previous generation's activities. Increases in coal prices have led to old coal tips proving to be a source of further coal following washing operations. The advent of zinc galvanising was associated with a short lived nineteenth and early twentieth century reworking of lead mine waste. It is perhaps now a matter of time before old landfill sites are being mined for some waste product of our throw away western culture (rare earth metals associated with batteries perhaps?). These are examples of changes of the economic value resulting from supply and demand changes, and technological breakthrough.

What is much harder to establish is what the effect will be on future geological scientific knowledge given the removal / sterilisation of unrecorded and / or undervalued elements of our geological heritage. In terms relating to specific aspects of the Hirnantian outcrop in the Welsh Basin it is worth asking what scientific data might be hiding in the rock record, waiting to be discovered and utilised in the future.

There are potential simple economic values associated with the Hirnantian, and closely associated rock outcrop. Since the late 19th Century it has been apparent that "unconventional plays" in both oil and gas reservoirs, have potential sources in

Ordovician and Silurian rocks. Furthermore rocks of near this age are a known historical source of phosphates in Wales (Penygarnedd, Tanat Valley) and are associated with oolithic ironstones throughout North Wales (Trythall 1988). The slightly younger Ludlow rocks which outcrop near Llangollen are notably spotted, and the spots are recorded to be enriched in rare earth elements.

Considerably further afield, rocks of Hirnantian age are being investigated for the presence of what are termed "Hot" shales – associated with enrichment of organic carbon and potential hydrocarbon source rocks (Armstrong, Abbott et al. 2009). It would appear to be fair to suggest then that almost any rock type has the potential to be the subject of increased economic value, associated with as yet imprecisely defined changes in supply and demand, for any number of potential undefined future mineral uses.

7.5 Geoconservation as an active philosophy

The significance of the findings of this thesis needs to be considered against the background of progress within both the Geoconservation Community, and against a wider societal background. In times of austerity and funding shortfalls, and it would appear with climate change denial become an increasingly acceptable position to hold for those in politics, the question must be asked "Who cares? Why should they care? How should they care?" (Nicholls and Burek 2015)

Whilst many aspects of those philosophies that form Geoconservation are common to the wider ecological or environmental mind-set, it is notable that as a formal academic discipline, Geoconservation is a relatively young subject and consequently remains immature (Burek and Prosser 2008). The relative youth is illustrated by the graph below (Figure 7.7) showing the variation with time of "hits" for the word "Geoconservation" in Science Direct searches between 1998 and 2016.

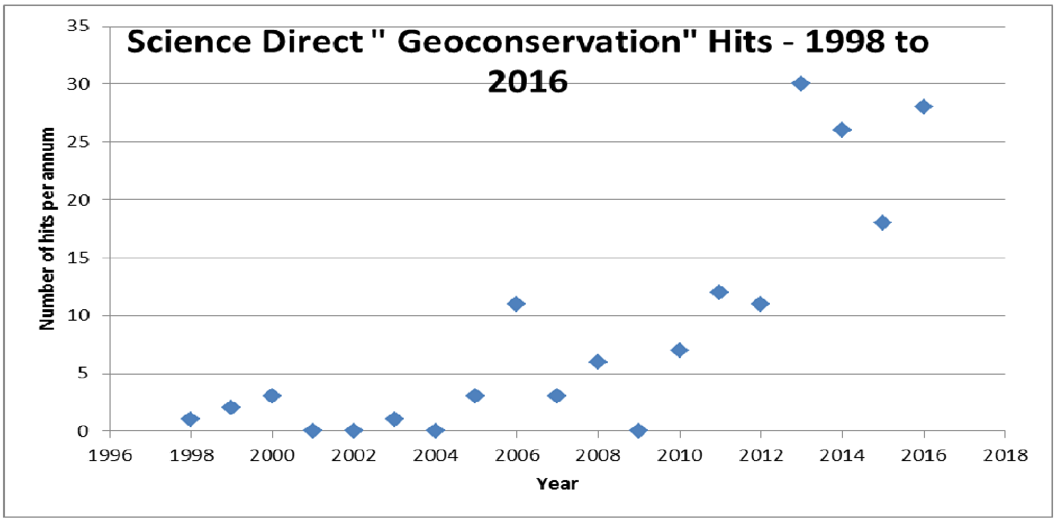


Figure 7.7 Growth in Science Direct citations with "Geoconservation" in subject titles – 1998 to 2016

From a point of zero hits in 1996 there has been consistent and ongoing growth as interest in the subject has waxed. Whilst some of the increase can probably be considered as a consequence of growth in publication quantity and accessibility associated with the advent of the internet, the almost exponential increase seen post 2010 does appear to relate to a genuine increase in the particular subject. The consequent immaturity is evident however in the current arrangements for oversight within the Geoconservation Community, with interest, activity and responsibility split between a number of organisations. Jefferies (2006) showed a similar graphic illustrating the appearance of "biodiversity" in Web of Knowledge citations which showed the point of rapid growth occurring in the early 1990s, implying that the Geoconservation movement is perhaps a decade behind the Bioconservation movement.

GeoconservationUK (GCUK) represents a putative national oversight body, but it is heavily dependent for its existence on the good will of its members, and their supporting institutions (both academic and in business). There are similar aims within other nationally relevant organisations, to the extent that they can be seen to be almost in competition with GCUK. Both the Geoconservation Committee of the Geological Society of London, and the county based Geology and local Geological Trusts have similar roles, and indeed in some cases a common membership.

Similarly the extent of coverage of the legislative arrangements varies nationally between the constituent devolved nations of the United Kingdom, and between the marine and terrestrial environments, as recorded by Burek, Ellis, Evans, Hart, and Larwood (2013). This latter point has been repeated more recently by Brooks, Chaniotis, James, Kenyon, Leslie, Long and Rennie (2016) who stated "*Until recently, in Scotland and elsewhere, marine geoconservation has received relatively little attention compared to the conservation of geoheritage in the terrestrial environment"*.

Earlier in this Chapter (Figure 7.5) the existence of a series of "sets" of sites was put forward. The aims and objectives of all those active in the Geoconservation community can be considered against this Figure – with a view to "conserving" the available Earth Heritage resource - by ensuring that the GCR / SSSI / RIGS sets are not compromised by infrastructure development, mineral extraction or the myriad other threats that today's society poses to the geological and geomorphological sites that we are concerned with. It is evident however that the act of "conserving" the available heritage resource, is different to the act of actively broadening or widening the available resource. Figure 7.9 below illustrates how the various members of the Geoconservation community interact.

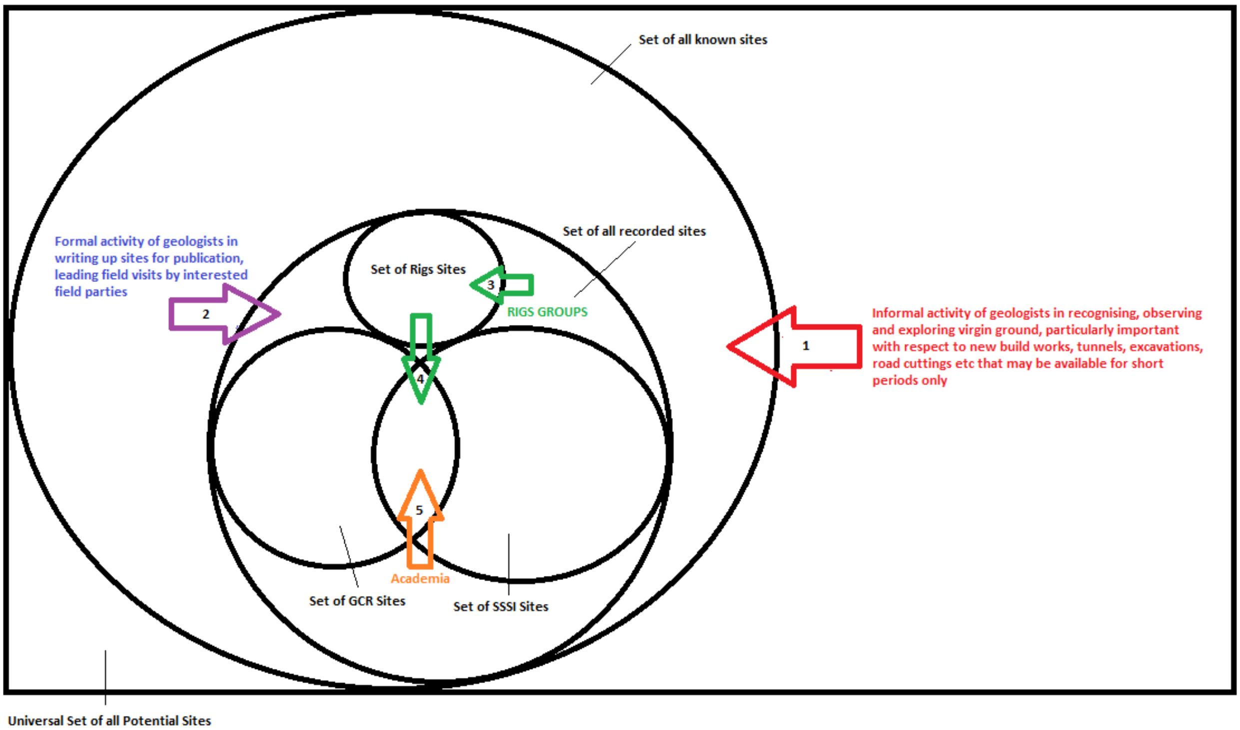


Figure 7.8: The Geoconservation Linkages: Interaction between geologists, academia, and the geoconservation community

Linkage 1 - This represents the activity of all geologists who interact with “virgin” ground that does not form part of the established geological background lexicon. This does not only occur when “mapping” new ground, but is also a widespread occurrence when new ground is broken during development work, or excavated during extraction, and indeed when exposed as a consequence of natural events (mass movement, subsidence etc). As a group the geotechnical community who act within civil and mining engineering are probably those with the most untapped potential to bring sites into the “known” category.

As an example of the kind of opportunity Inset Box 7.1 includes a description of rock core obtained from a site at Barlockhart Moor, Dumfries and Galloway (Rhuddanian). This was made available at the request of the author by West Coast Energy, as a consequence of my role in site investigation for a proposed wind farm site. In the vast majority of cases however this information will pass into a private archive, and be effectively lost. In this particular case of course, its inclusion in this thesis serves to take it into the next “recorded sites” category.

Inset Box 3 Barlockhart Moor, Scotland

Private farm land (rough sheep grazing) under development by West Coast Energy as site of wind farm. No public access to site, core taken by Geotechnics Ltd on behalf of West Coast Energy, through Arup Geotechnics. These have been made available for study courtesy of West Coast Energy.

Gala Unit 1. Turbidite mudstone from Laurentian seaboard (Western coast) of Iapetus Ocean. Relatively deep water sediments. Rhuddanian turbidites sourced from Laurentian shelf. Can be correlated with Cwmere / Allt Goch Formations of the Welsh Basin.

Represent Iapetus deepwater sediments associated with the post "*persculptus*" transgressive system tract.

A point of concern is the fact that sites can be lost permanently from the universal set of all potential sites without ever interfacing with the geological community. Nicholls and Burek (2015) record an instance from Porthmadog, Gwynedd, where a Cambrian trace fossil from the Ffestiniog Flags was recovered from a road sub-base stockpile by a passing geologist (Heiland 2014). It is a matter of concern that due to the modern prevalence of "Design and Build", and Contractor led procurement in civil engineering in general, that the role of the Consulting Engineer as an impartial observer acting on behalf of the Client has been diminished. It is discouraging to think about the quality and importance of fossil specimens, key sedimentological or structural features etc. that have been, and are being lost, unwittingly and unintentionally perhaps, but regularly, during the course of site investigation and construction works.

Linkage 2 – The importance of publication of observations and site descriptions cannot be over emphasised. Without formal record of observations there is little prospect of a "known site" becoming a candidate for formal designation as a GCR or SSSI site –

irrespective of the nature of the content of that material. Publications such as the Proceedings of the Yorkshire Geological Society, North West Geologist and the Proceedings of the Geologists' Association etc. do offer some potential for the rapid dissemination of material, but these are typically not widely read by those in the geotechnical community. Lower key publications such as Geoscientist and Earth Heritage do offer some scope for such publication, although again are not widely read by those of us who work in the geotechnical community. The active publication of Geoconservation related work in the Proceedings of the Geologists' Association is a welcome change, but this readily accessible resource is perhaps surprisingly, not frequently referred to in the Geotechnical Community. Considerably more work to follow Burek and Hope (2010) to engage directly with the geotechnical community is required.

The point however is clear, that the majority of interactions with the natural physical heritage resource made by those in the geotechnical community rarely move out of the "known site" set into the published lexicon. The reasons for this are complex but in my experience I have encountered the following barriers:

- Limited knowledge within the geotechnical community of the Geoconservation perspective associated with their work

- Time / budget issues associated with anything considered to be "extra over" minimum acceptable deliverables

- Reticence of Client bodies to permit publication due to liability concerns

- Lack of confidence amongst those in the geotechnical community with respect to their ability to engage with academia, or to write with appropriate rigour for publication.

- Confidentiality of Client "owned" materials and intellectual property

Potential solutions to this lack of interaction between academia and industry will require action from both parties. Within academia work must be done to interact with those undertaken drilling and sampling up and down the country on a regular basis. Hundreds of tonnes of cored material are disposed of into skips every month up and down the country by Site Investigation Contractors needing to keep core stores clear for newly arrived material. The sampling is paid for by government agencies (Highway Authorities, Network Rail, the Nuclear Industry, as well as small and large scale private developers). In the absence of formal legislative requirements to lodge investigation data it rests with academics to let industry know their interest in seeing specific cores types ("I'm interested in, for examples: the *subcrenatum* marine band.. the Kimmeridge Clay.. the lowermost Silurian..etc.".

From industry's perspective if asked they should be willing to make core available for inspection, to ask client's permission to pass on samples, and Intellectual Property, but above all industry should try to engage with the academia by getting involved in research projects, by writing for publication, and keeping up with published material. Support for their local RIGS group, or other Geoconservation body would be a considerable benefit, with significant advantages for both parties (Nicholls and Burek 2015)

Linkage 3 – This represents the work undertaken by the regional RIGS groups. A detailed summary of the work undertaken by the RIGS groups in Wales up until 2008 was described by 2008 (Burek, 2008). It is entirely dependent on the particular group's level of activity, the availability of resources to it, and the energy, commitment and skill set of the individuals involved in the group. Within Wales RIGS activity has been subdivided on a regional basis, and the degree to which these can be considered as fit for purpose at the present time varies considerably. In summary, the five regional groupings are:

- Gwynedd and Môn RIGS – active in North West Wales (including Snowdonia and Anglesey (Ynys Môn))
- NEWRIGS – active in North East Wales
- Mid Wales – active in the counties of Powys and Ceredigion
- South West Wales – inactive
- South Wales - re-established in 2015

There are current moves to split Gwynedd and Môn RIGS into separately constituted groups in Gwynedd, and Ynys Môn; with the UNESCO ratified (2015) GeoMôn Geopark taking responsibility for RIGS work on Anglesey. Appendix 5 includes a proposed RIGS site at Coed Tal y Llyn / Llyn Geirionydd which will be the first formal proposal to be considered by the putative Gwynedd RIGS Group on its establishment in due course. The impact of Geopark listing in the UK is generally considered positive, with 7 such sites in the UK (Shetland, North West Highlands, Marble Arch Caves, North Pennines AONB, GeoMôn, Fforest Fawr and English Riviera) are generally considered positive; as stated by Prosser:

> *"Global Geoparks help to protect and promote geodiversity through geoconservation but also use geodiversity to promote sustainable development and geotourism and to engage local communities in enjoying and promoting their local geological heritage.*" (Prosser 2013)

The impact of the Geopark is certainly positive with respect to the geodiversity within the boundaries of the defined Geopark boundaries. However, the question as to whether the Geopark acts to lessen overall geoconservation remains open. It is certainly the case that despite containing some of the globally most important geological sites (Cwm Idwal, Nant Ffrancon, Cader Idris, Bala, etc.) Snowdonia has not received anything like the Geoconservation attention afforded to Anglesey since the establishment of the Geopark.

In 2007 Wood published a catalogue of the then notified RIGS sites in the Gwynedd & Môn area (Wood 2007). Figure 9.5 below illustrates the split of sites between Gwynedd and Anglesey, and also within the somewhat arbitrary sub-divisions (or "Networks") established therein. Approximately 2/3 of the designated sites are in Anglesey / Môn. The imbalance is even more apparent when it is noted that all the 31 sites in the Gwynedd "Geological Sites" Network (i.e. almost 50% of the Gwynedd total) were established as a consequence of the "Minescan" funding stream from the former Countryside Council for Wales and National Museums of Wales.

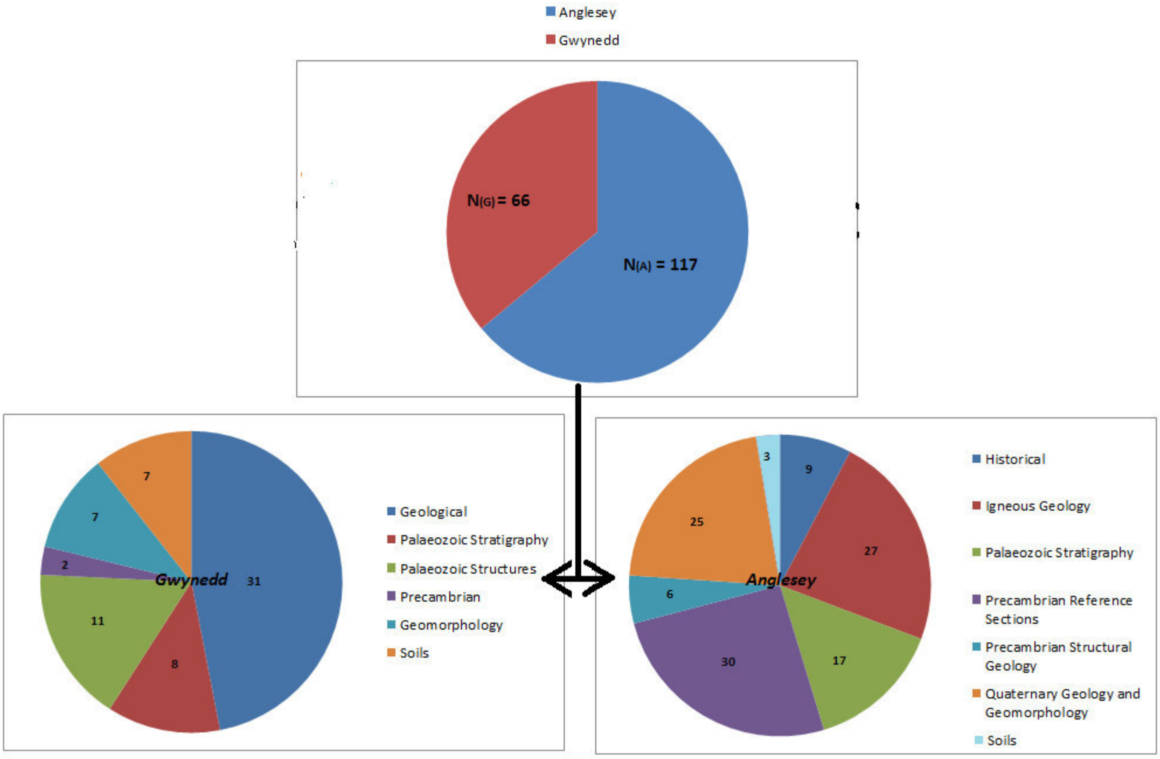


Figure 7.9: Gwynedd and Môn notified RIGS sites (2007) showing relative predominance of Anglesey over Gwynedd, and range of Networks covered.

Larwood et al have reported that funding of the seven UK Geoparks exceeds £13M (with £3.2M for the Marble Arch Caves, and £5.4M for the English Riviera). If the funding stream that Geoparks secure is because of diversion from other geoconservation activity, rather than an addition to existing funding, then it should be viewed with concern from the wider perspective.

NEWRIGS remains active, but it is clear from Figure 7.10 (below) that its notification activity (surely the key activity of any RIGS group) is cyclical, with clear "boom and bust" cycles in the notification of RIGS sites to the relevant Local Authorities. The impact of the "Minescan" Survey is clearly identifiable, as is the case with the Gwynedd and Môn notications. However, there may come a time when most of the sites have been notified and it will only be the excavation of new areas (roads, housing estates industrial complexes etc) that leads to new recommendations for designation. When the designation and maintenance of sites is sustainable it then becomes the duty of the RIGS group to educate and inform the relevant people. This is one of the recognised stages of successful geoconservation as stated by Burek & Prosser (2008).

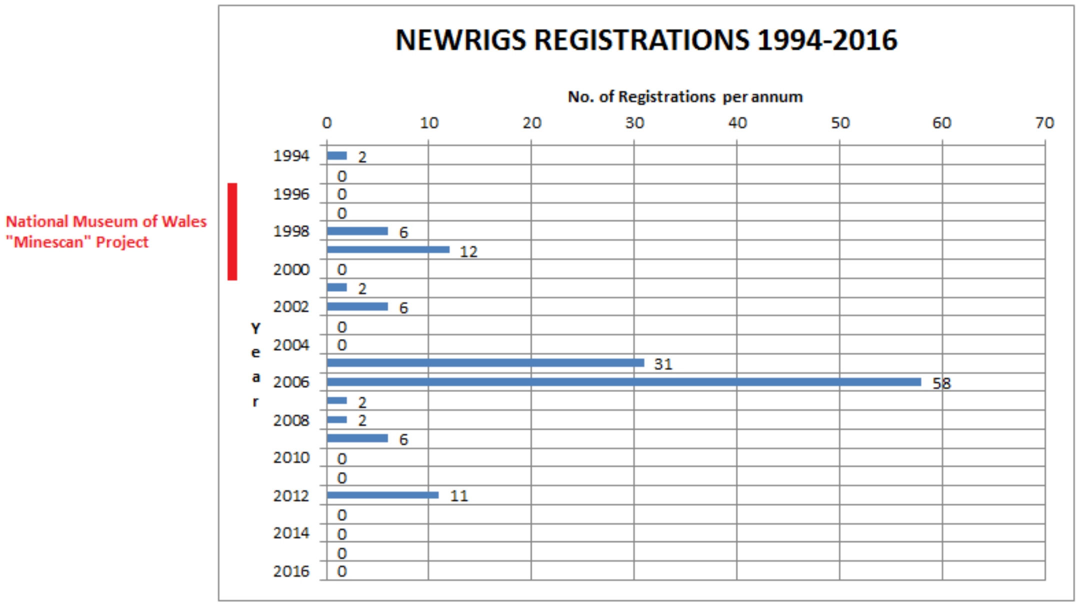


Figure 7.10: Designation activity within NEWRIGS

The Mid Wales RIGS group is alone amongst the existing RIGS groups in Wales in offering a publicly accessible web site, with formal RIGS Statement of Interest for all its designated sites (listed separately on a County basis (Powys or Ceredigion)).

The South West Wales RIGS group is currently entirely inactive, despite the region's rich geological heritage. The two former counties of Carmarthenshire and Pembrokeshire host a diverse assemblage of rocks and soils, from Pre-Cambrian to Holocene, and iconic elements of Wales natural heritage including the Green Bridge of Wales, the St. David's Peninsula, and the apparent source in the Preseli Hills of the Stonehenge "Bluestones". The lack of an active RIGS group was brought into focus in 2016 by events surrounding an active archaeological dig at Rhosyfelin (Pembrokeshire). Concerns with respect to the potential impact of archaeological work on a potential quarry site associated with bluestone excavation led to the Association of Welsh RIGS Groups (AWRG – now known as Geoconservation Wales – GCW) being asked to designate the site to establish its geological potential, alongside its obvious archaeological interest. This has required a redrafting of the AWRG / GCW constitution, allowing it to act with *de facto* national oversight, in the absence of a local group.

The South Wales RIGS group has been re-established recently (2015) as an active third sector grouping following the loss of Aggregates Levy funding which had been secured by the British Geological Survey to undertake a formal audit of their region, which includes of course, remnants of the Old Red Sandstone Continent, the South Wales Coalfield, important tracts of Mesozoic strata around the Vale of Glamorgan, and extensive glacial and post-glacial sediments. One unfortunate outcome of the removal of funding prior to publication of the formal BGS audits is the unavailability of the site records to date. GCW and the newly established South Wales RIGS group are hoping to clarify this situation in the coming Mônths, but at the time of writing the question of public accessibility to this publicly funded research work remains unresolved (as at January 2019).

With respect to the Hirnantian outcrop across Wales only the South Wales RIGS area is not relevant. Consequently, formal geoconservation work associated with the Hirnantian outcrop as a whole needs to engage with an active RIGS group in each of Gwynedd & Môn (primarily the Gwynedd sector), NEWRIGS, Mid Wales and South West Wales.

Linkage 4 – Perhaps the ultimate illustration of the worth of a RIGS groups to the wider geological community, and to society at large, is the potential for sites brought forward as RIGS sites to be deemed of sufficient import to be picked up by the Statutory Conservation Authority (NRW in Wales) and taken forward as a SSSI. This is illustrated to great effect by the recent establishment of the Brymbo Fossil Forest SSSI near Wrexham, following initial RIGS notification and considerable work from NEWRIGS and other groups (Figure 9.8 below).

Figure 7.11: Wrexham Museum display materials associated with the Brymbo Fossil Forest SSSI, comprising the trunk and root system (approximately 2m high) of a Giant Horsetail (*Calamites*) and leaf debris including a specimen of *Annularia stellata* (top right) and a number of *Alethopteris serli* (field of view approximately 10cm)

Linkage 5 – This represents the case where research work, or sometimes mere chance identifies key localities that are of sufficient merit that they are taken forward directly as potential SSSI sites, requiring the proposal to be put forward by relevant academics direct to the Conservation Authority (NRW). Appendix 5 includes a proposed SSSI site at

Cilborth Beach, Llangrannog, put forward as a result of the research described earlier in this thesis that is currently under review by NRW.

In two recent papers attempting to establish strategies for future geoconservation (Erikstad 2013) and Larwood Badman and McGeever (2013) make the following points:

> *"Future strategies for geoconservation must acknowledge the complexity of the field both with respect to scale and to varying scientific requirements"* and,
> *"It is still of vital importance to appreciate that geoheritage, geodiversity and geoconservation are not accepted theoretically or practically in most countries of the world. Therefore the basic promotion of these concepts should still have a first priority in the years to come."*
>
> "*The geological community needs to work more effectively together and connect beyond this community"*

It is important that those of us concerned with regards to future geoconservation in the UK understand the routes that need to be taken to formalise protection for our natural heritage. It is surely the responsibility of the whole geological community to maximise the growth of each sub-set of sites within the universal set of all potential sites, by visiting, and recording sites of geological interest, and doing what each of us can to conserve the soil and rock record where we can. There should be greater use of opportunities for publication and formalised site record keeping that draw in the geotechnical community (for example see the "GeoExposures" crowd sourcing tool being promoted by the British Geological Survey (Powell, Nash et al. 2013)) to aid in establishing a "bottom–up" driver to maximise the ratio of recorded sites to known sites.

It is important that RIGS and other geoconservation groups continue to consider, and where appropriate, designate new RIGS sites (in Wales, "Local" sites in England) and also that if sites are thought to be of sufficient standing that they pass their information on to the relevant Statutory Authority to consider for SSSI listing as deemed relevant.

7.6 Geoconservation in a time of austerity:

The Global Financial Crisis (GFC) of 2008 (and beyond) has resulted in a sea change in attitude towards public spending and investment by local and central government. The consequence of this has been both:

1. a tightening of government purse strings, and

2. a lessening of available finance as a consequence of low interest rates and minimal profit margins in the private sector.

A number of early phases of designation of RIGS sites, and indeed the initial phase of the comprehensive Geological Conservation Review were associated with funded activity. It is apparent that if Geoconservation is to survive (even perhaps to thrive?) in the post GFC economy it will rely increasingly on voluntary contributions from its membership (Burek 2008) and it will need to work in a lean and efficient manner. It is absolutely vital that the Geoconservation community present a coherent and structured argument when dealing with other agencies, and that the arguments made are put forward professionally. The charge has been made that as a group there is a tendency for "*the conservation sector to talk to itself and to shout at everybody else*" and that "*Simple assertion of our version of the truth, however well founded in fact, will not convince and tends to alienate*" (Wood 2013). This comment, even if intended as a generalised challenge rather than a statement of fact, needs to be borne in mind, coming as it did from the Executive Director (Science, Evidence and Advice) of Natural England. Thus there is further duty on RIGS and the other geoconservation groups to tell the story to others, through for example public lectures, outreach activities and generally raising awareness of geoheritage and Geoconservation issues to the public at large. The importance of appropriate communication strategies has been understood by the bioconservation movement for some time with Spellerberg (1996) stating:

> *"Since the public wants their politicians to deliver benefits not constraints, conservation biologists advocating policy changes need to become much more politically and economically astute if they wish to have the impact they desire"*

A key component of any such progress must be the establishment of a Geodiversity Charter for Wales to follow the recent publications of similar documents by the Scottish Geodiversity Forum (SGF 2013) and the English Geodiversity Forum (EGF 2014). The author has been closely involved with the development of proposals to publish a Geodiversity Charter for Wales, and a Draft document is currently in preparation by members of Geodiversity Wales. Nevertheless, the pressures on potential public funding streams are considerable, and these have resulted in the following recent statement from WAG in respect of the Aggregates Levy Fund:

> *The Aggregate Levy was introduced in 2002 as a 'green' tax on the commercial extraction of aggregate – hard rock, sand, gravel and shale. A proportion of the revenue raised has been used to support capital projects in communities affected by active aggregate extraction.*
>
> *I have considered the future sustainability of the Fund against the background of resources available for the period 2017-21. The equivalent scheme in England closed in 2011 as a direct consequence of initial austerity cuts. In Wales we have sought to maintain the Fund for as long as possible.*
>
> *This year the Welsh Government is once again faced with difficult spending decisions against a background of competing strategic priorities, and hard choices have had to be made. The budget available to the Fund has now dropped to the point where its impact has become limited. Regrettably, therefore, I have made the decision to close the Fund with effect from 31 March 2017.*
> Lesley Griffiths WAG Assembly Member with responsibility for Environment and Rural Affairs

One significant point that needs to be addressed however as the Charter develops is the lack of specific reference to trace fossils in some of the associated geoconservation collection advice. Both the Scottish Geodiversity Charter (SGC) and the Geodiversity Charter for England (GCE) comment that collection should be undertaken in accordance with existing guidance, without specific reference to that guidance. In Scotland a Scottish Fossil Code has been published separately by Scottish Natural Heritage (SNH 2008) and specifically places trace fossils as a sub-set of the broader collective of "fossils" in general, warranting therefore the same level of protection. There is no equivalent national guidance in England although there is a specific regional publication in West Dorset and a general guide to fieldwork published by the Geologist's Association which requires collection of "fossils" to be kept to a minimum. Internationally the Society of Vertebrate Paleontology have published a set of standard procedures (SVP 2010) and perhaps not surprisingly given the importance of work on dinosaur trackways, make detailed and specific reference to traces, tracks nesting sites etc. It is surely the case that any omission of trace fossils from an overriding protection of fossils in general can only be as a result of omission by oversight, since many museums include trace fossil specimens as key items of their displays.

7.7 Geovalue as a key component of Natural Capital

The concept of "Geovalue" (sensu Nicholls) defines the "scientific value" of a location's physical character as a tool for environmental monitoring and future research potential. This is a narrowly defined subset (or ecosystem service) of a wider concept established under the "Natural Capital Approach" (Voora and Venema 2008).

Natural Capital (NC) is defined as:

"NC is the natural environment from which emanates the goods and services that sustains life. More specifically, it is the basis for human activity and well-being. Therefore, human activity and well-being is closely coupled with the state of NC and its services. NC can be broadly described as renewable or non-renewable. Renewable or active NC is self-maintaining due to its ability to harness solar energy. Non-renewable or inactive NC are formed over long geological time periods and are passive. "NC includes both mineral and biological raw materials, renewable (solar and tidal) energy and fossil fuels, waste assimilation capacity, and vital life support functions (such as global climate regulation) provided by well-functioning ecosystems." Costanza and Daly (1992) compare renewable NC to machines that are subject to degradation while non-renewable NC is analogous to inventories which can be liquidated."

The consequent Natural Capital Approach (NCA) is defined as:

"A means for identifying and quantifying the natural environment and associated ecosystem services leading to better decision making for managing, preserving and restoring natural environments."

The argument I make is that the rocks of the Welsh Basin, and specifically the trace fossil record associated with the Hirnantian Glaciation and Extinction event is a non – renewable element of natural capital. Failure to offer an appropriate level of protection runs the risk of liquidating an inventory before we are able to fully understand its value.

In order to bring an appropriate level of protection to these rocks, and indeed other similarly important elements of Geological Natural Capital (GNC), it is my contention that a NCA is a necessary starting point. Voora and Venema (2008) detail NCA applications being promoted in China, Australia and Canada. Wales' government policy in this field is given by the 2015 "Well-being of future generations Act" which introduced a sustainable development principle (SDP). Seven key goals are set out in the Act and three of these can be taken to imply a need to develop a NCA as detailed in Table 7.5.

Table 7.4: Key Goals relating to NCA within WAG "Well-being of future generations Act (2015)"

Goal	Statement
A prosperous Wales	An innovative, productive and low carbon society which recognises the limits of the global environment and therefore uses resources efficiently and proportionately (including acting on climate change); and which develops a skilled and well-educated population in an economy which generates wealth and provides employment opportunities, allowing people to take advantage of the wealth generated through securing decent work.
A resilient Wales	A nation which maintains and enhances a biodiverse natural environment with healthy functioning ecosystems that support social, economic and ecological resilience and the capacity to adapt to change (for example climate change).
A globally responsible Wales	A nation which, when doing anything to improve the economic, social, environmental and cultural well-being of Wales, takes account of whether doing such a thing may make a positive contribution to global well-being.

These Goals are derived from an overarching SDP which requires bodies to:

"act in a manner which seeks to ensure that the needs of the present are met without compromising the ability of future generations to meet their own needs."

How the decision to close the Aggregates Levy Fund from March 31st 2017 sits within this legislative framework seems difficult to reconcile. The Sustainability Principle borrows heavily from Brundtland's definition (1987) of sustainability:

"Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs"

Such good intentions are frequently reported as part of a three pillared, or three centred approach which leads to "sustainable development" supported by each of the three contributory factors of economy, society and environment (Adams 2006). This viewpoint is important, and should be used to challenge decisions such as that made by the WAG to end support for environmental projects via the Aggregates Levy Fund in Wales. The Minister's comment that they are faced with "*difficult spending decisions against a background of competing strategic priorities"* shows that environment and society can be trumped by economic arguments. It is only by dealing in "natural capital" and making arguments based on the true costs and values of our geosystem services that the Geoconservation community will be able to prosper.

It is evident from recent publications that Geoconservation is of increasing interest on an international basis, with substantial recent publications describing work from as far afield as Inner Môngolia (Wang, L., Tian, M. et al. 2014), Romania (Neches 2016), New Zealand (Mignon and Pijet-Mignon 2016) and South Africa (Ruban 2012). Whilst Wales occupies a unique position with respect to its role in the historical development of the science of geology, and in many ways was at the forefront of early development of Geoconservation (see Burek 2008, Burek, 2012), we have fallen behind the other nations of Great Britain (SGF 2013; EGF 2014) in adopting a national Geodiversity Charter. There are considerable opportunities to be gained from taking a lead in promoting our rich geodiversity, and recognising the geosystem services that it underpins. Inaction however is likely to result in the lead being taken by other nations with a more vigorous understanding of the place of their geology.

7.8 Geoconservation and a place in Society

A significant problem facing the Geoconservation community is an apparent lack of interest from the general public toward our abiotic natural heritage, and a lack of understanding of our broad geosystem services from both the general public, and in particular those involved in the legislative process. Despite the frequent presence on prime time television of David Attenborough, Brian Cox, Alice Roberts and Ian Stewart, often presenting matters of geological origin, and huge social and economic import, there is relatively little direct public engagement with ordinary members of the ordinarily "unengaged" public, and maintenance of the *status quo* risks us all being seen as preaching to the converted. This must become an important part of the overall work of the Geoconservation community, with RIGS and other voluntary geoconservation groups needing to be at the forefront of this activity.

Some fault for the current situation must lie with those of us in the Geoconservation community, not through lack of interest, or indeed of effort. The problem would appear to have been a failure to make geology, and more generally earth sciences, directly relevant and accessible to the general public, and our elected representatives. In his book Rock of Ages (1999) Stephen Jay Gould identifies the dual track system he calls "NOMA", or "non-overlapping magisteria", in which he identifies separate thought systems adopted by those in the sciences, and those in the humanities. Whilst actively discouraging any "*Never the twain shall meet*" scenario Gould states that it is necessary to respect both systems, and communicate effectively between. It is worth noting that few geology courses offer formal training to undergraduates in Geoconservation, a point made by Burek (2011) and requiring address in future years if we are to make a success of our efforts. Table 7.6 below identifies the current WAG Cabinet Ministers and identifies their academic backgrounds

Table 7.5 WAG Cabinet Members* and their educational background

Individual	Role	Background
Carwyn Jones	First Minister	Law / Barrister
Mark Drakeford	Finance and Local Government	Social Policy
Vaughan Gething	Health Well-being and Sport	Law
Lesley Griffiths	Environment & Rural Affairs	Health
Jane Hutt	Leader of the House and Chief Whip	Economics
Carl Sargeant	Communities and Children	Engineering
Ken Skates	Economy and Infrastructure	Social / Political Science
Kirsty Williams	Education	History / PR
Mick Antoniw	Counsel General	Law

*Table prepared prior to the suicide of Carl Sargeant, and the announcement that Carwyn Jones intends to stand down as First Minister.

A brief review of the above clearly indicates that if the Geoconservation community in Wales wishes to engage in a meaningful manner with our policy makers it is important that we understand that it is necessary to engage in a manner that is appropriate to those whose backgrounds are primarily in the humanities and social sciences. Looking overseas of course the extent of the dichotomy between the backgrounds of those in power and their understanding of scientific principles has been thrown into sharp focus by the 2017 appointments within the Trump administration, and in particular with the placement of Scott Pruitt to head up the EPA, and Betsy de Vos having responsibility for Education.

7.9 Further work required

At the outset of this study it was determined that success could be judged by the principal "deliverable" items comprising new RIGS or SSSI sites that could be proposed as a result. Three such sites have been proposed (as detailed in Appendix 5). These are:

- a new SSSI at Cilborth Beach, specifically related to the trace fossil assemblage to partner the existing Aberarth = Carreg Wylan SSSI, and RIGS site.

- a new RIGS site at Cwm Hirnant to extend the protection afforded by the Chwarel Cwm Hirnant SSSI to the adjacent areas and in particular to acknowledge the potential of the Bwlch yr Hwch section, and

- a new RIGS site at Coed Tal-y-llyn in the slightly older mid to late Caradoc (Katian) rocks associated with the Nod Glas horizon. This site yields significant evidence of primary sulphide mineralisation, as well as an evident mass mortality event in the *clingani* graptolite stage.

The documents in Appendix 5 have been prepared and offered to respectively NRW, NEWRIGS and the newly established "Gwynedd RIGS" group. Unfortunately each proposal is currently held in abeyance with NRW being in the process of changing their SSSI proposal forms, doubts existing as to the area of responsibility covered by the NEWRIGS group, and a delay as a consequence of the recent establishment of the Gwynedd RIGS group, spun out from the Gwynedd and Mon RIGS group.

A key element to come out of this study is the recognition of the concept of Geosystem services, and the "Geovalue" that is one element of the overall geosystem services that our abiotic nature provides. The statement that our geodiversity underpins our biodiversity is often stated, and is true. However, it is also the case that our geodiversity underpins our economy, our physical infrastructure and in many ways therefore, our entire society.

Further work is required to establish the true "value" of our rock (and indeed soil) record in providing tourism, minerals, research opportunities, climate moderation, coastal protection etc. At the present time it is apparent that, other than as mineral products, there is little acknowledgement of the true value of our geology, and the geoservices they provide.

The Hirnantian rocks of the Welsh Basin offer considerable potential for further scientific research into extinction processes, palaeoecology and stratigraphy. The Hirnant Limestone especially appears to be a seemingly understudied resource in terms of what it can offer micro-palaeontologists in terms of its fossil content. There has been considerable research recently published in respect of the Sholeshook Limestone (see for example Baars 2013) which is a somewhat older rock Cautleyan / Rawtheyan (Price 1980), but of similar nature. A comparative study between the two could be extremely useful in linking or denying their shared origin in an intermittent “ice-house” Ordovician world.

The comparative deep water sections of the basin (ie at Llangrannog) offer potential for detailed chemostratigraphic work to identify the potential presence of the HICE excursion. This could be identified directly by assessment of whole rock organic carbon isotope analyses, or indirectly by future strontium analysis. Conversations with a number of practitioners of cyclostratigraphy held during the IGCP field trip (Summer 2016) suggested there may also be significant potential for the detailed sedimentary structures apparent in the superb coastal exposure to yield good data in their particular field of study, potentially shedding significant light on the Hirnantian and early Llandovery palaeoclimate.

The extent of soft sediment deformation in the Brynglas Formation, appears to be controlled by the presence of “debrite” beds within the underlying Drosgol Formation. Together with the presence of substantial dewatering features in the sediments these are indicative of a major latest Hirnantian slope failure in the shelf sediments of the western Avalonian margin. The presence of consequent tsunami style deposits of *persculptus* age in sediments elsewhere in the epieric Iapetus Ocean are considered probable and as such others may wish to look for such event beds in *persculptus* zone rocks of the Irish Caledonides, and in the Laurentian - Appalachian strata.

The trace fossils themselves described herein are a substantial untapped resource for further detailed analysis. I have only, like others before me (see this Chapter’s frontispiece comment by Richard Twitchett) scratched the surface. Further stratigraphic work is being pursued at the moment and it is likely that the Hirnantian stratigraphic framework established in this thesis (Drosgol and Brynglas Formations between the Nantmel and Allt Goch Formations) will be revised as a result in the near future. It is as a direct result of the observations relating to the trace fossils that has made this ongoing revision possible, and this is a clear example of the Geovalue of this fundamental research in aiding scientific progress.

REFERENCES

Adams, W.M., (2006) "The Future of Sustainability: Re-thinking Environment and development in the Twenty-first Century". *Report of the IUCN Renowned Thinkers Meeting*, 29-31 January 2006, World Conservation Union.

Agicola G. (1556) "De Re Metallica", Translated from the First Latin Edition by Herbert Clark Hoover & Lou Henry Hoover, The Project Gutenberg EBook of De Re Metallica, published November 14, 2011

Ainsaar, L., D. Kaljo, T. Martma, T. Meidla, P Mannik, J. Nolvak and O Tinn (2010). "Middle and Upper Ordovician carbon isotope chemostratigraphy in Baltoscandia: A correlation standard and clues to environmental history." Palaeogeography, Palaeoclimatology, Palaeoecology **294**(3-4): 189-201.

Anketell, J. M. (1987). "On the geological succession and structure of South–Central Wales." Geological Journal **22**(S1): 155-165.

Anon (Undated). Chwarel Cwn Hirnant: your Special Site and its future, Cyngor Cefn Gwlad Cymru Countryside Council for Wales.

Anon (2002), "Ceredigion And Pembrokeshire Aberarth – Carreg Wylan", Site Of Special Scientific Interest: Management Statement, Cyngor Cefn Gwlad Cymru, Countryside Council For Wales.

Arkel, W. (1947). *The Geology of the Country around Weymouth, Swanage, Corfe and Lulworth*. London, Institute of Geological Sciences.

Armstrong, H. A. (1996). "Biotic recovery after mass extinction: the role of climate and ocean-state in the post-glacial (Late Ordovician - Early Silurian) recovery of the conodonts" Biotic recovery from mass extinction events. M.B.Hart (Ed.). London, Geological Society of London. 102: 105-117.

Armstrong, H. A., G. D. Abbott, et al. (2009). "Black shale deposition in an Upper Ordovician–Silurian permanently stratified, peri-glacial basin, southern Jordan." Palaeogeography, Palaeoclimatology, Palaeoecology **273**(3-4): 368-377.

Baars, C. (2013). "Rugose corals from the Upper Ordovician Sholeshook Limestone of southwest Wales with an assessment of the coral affinities and biofacies" Geological Journal **48**: 603-619.

Bambach, R.K., A.M. Bush and D.H. Erwin (2007) "Autoecology and the filling of ecospace: key metazoan radiations" Palaeontology **50**, 1-22.

Bancroft, B. B. (1933). Correlation tables of the stages Costonian - Onnian in England and Wales. Cheshire, self published.

Barnosky, A.D., N.Matzke, S.Tomiya, G.O.U.Wogan, B.Swartz, T.B.Quental, C.Marshall, J. L. McGuire, E. L. Lindsey, K. C. Maguire, B. Mersey and E. A. Ferrer (2011) "Has the Earth's sixth mass extinction already arrived?", Nat u r e **471.**

Basan, P. B., C. K. Chamberlain, R.W. Frey, J.D. Howard, A. Seilacher and J.E Warme. (1978). Trace Fossil Concepts. Oklahoma, Society of Economic Paleontologists and Mineralogists Short Course, **5**.

Bassett, D. A., H. B. Whittington and A. Williams (1966). "The stratigraphy of the Bala District, Merionethshire." Quarterly Journal of the Geological Society of London **122**: 219-271.

Bengtson, S. (1988). "Open Nomenclature." Palaeontology **31**(Part 1): 223-227.

Bergström, S. M., S. C. Finney, C. Xu, D. Goldman and SA. Leslie (2006). "Three new Ordovician global stage names." Lethaia 39(4): 287-288.

Bergström, S. M. and Ferretti A. (2014). "Conodonts in the Upper Ordovician Keisley Limestone of northern England: taxonomy, biostratigraphical significance and biogeographical relationships", Papers in Palaeontology. John Wiley & Sons Ltd.

Blanpied,C., M. Deynoux, J.-F. Ghienne, J.L. Rubino (2000). Late Ordovician glacially related depositional systems of the Gargaf Uplift (Libya) and comparisons with correlative deposits in the Taoudeni Basin (Mauritania). Geological Exploration in Murzuq Basin. M. A. Sola and D. Worsley. Amsterdam, Elsevier Science B.V.: 485-507.

Bockelie, J. F., B. T. Larsen and S. Olaussen (2008). The Palaeozoic geology of the Oslo Region, The Inner Oslofjord area, Notes to the localities, map and photos. I. G. Congress.

Bosence W.J and P, Allison (1995) Marine Palaeoenvironmental Analysis from Fossils. Geological Society Special Publication **83**. Geological Society of London

Botting, J. P., L. A. Muir, et al. (2012). "Diverse middle Ordovician palaeoscolecidan worms from the Builth-Llandrindod Inlier of central Wales." Palaeontology **55**(3): 501-528.

Botting, J. P. (2004). "An exceptional Caradoc sponge fauna from the Llanfawr Quarries, central Wales,and phylogenetic implications." Journal of Systematic Palaeontology **2** (1)(March): 31-63.

Bottjer, D. J., K. A. Cambell, K.A. Schubert and M.L. Droser (1995). "Palaeoecological models, non-uniformitarianism and tracking the changing ecology of the past". Marine Palaeoenvironmental Analysis from Fossils. W. J. Bosence and P. A. Allinson. London, Geological Society Special Publication **83:** 7-26.

Boucot, A. J. and J. Gray (2001). "A critique of Phanerozoic climatic models involving changes in the CO2 content of the atmosphere." Earth Science Reviews **56**: 1-159.

Boyer, S.E. and D. Elliott (1982) “Thrust Systems”. Bulletin of the American Association of Petroleum Geologists **66:** 1196-1230.

Brenchley, P.J., J.M.D. Marshall, D.A.T. Harper, C.J. Buttler and C.J. Underwood (2006). "A late Ordovician (Hirnantian) karstic surface in a submarine channel, recording glacio-eustatic sea-level changes: Meifod, central Wales." Geological Journal **41**: 1-22.

Brenchley, P. J. and G. Newall (1980). "A facies analysis of upper Ordovician regressive sequences in the Oslo Region, Norway -- A record of glacio-eustatic changes." Palaeogeography, Palaeoclimatology, Palaeoecology **31**: 1-38.

Brenchley, P. J. and R. K. Pickerill (1993). "Animal—sediment relationships in the Ordovician and Silurian of the Welsh Basin." Proceedings of the Geologists' Association **104**(2): 81-93.

Brenchley, P.J., G.A. Carden, L. Hints, D. Kaljo, J.D. Marshall, T. Martma, T. Meidla and J. Nõlvak (2003). "High-resolution stable isotope stratigraphy of Upper Ordovician sequences: Constraints on the timing of bioevents and environmental changes associated with mass extinction and glaciation." Bulletin of the Geological Society of America, **115** (January, No 1): 89-104.

Briggs, D. E. G. and P. R. Crowther (1990). Palaeobiology: a synthesis, Blackwell Science.

Bromley, R. G. (1990). Trace Fossils: biology and taphonomy. London, Unwin Hyman Ltd.

Brundtland, G.H. (1987) "Report of the World Commission on Environment and Development: Our Common Future". United Nations.

Buatois, L. A. and M. Gabriela Mángano (2011). “Ichnology: Organism-substrate Interactions in Space and Time”. Cambridge, Cambridge University Press.

Burek, C.V. (2008). "The role of the voluntary sector in the evolving geoconservation movement." Burek, C.V. and Prosser, C.D. (eds.) The History of Geoconservation, Geological Society of London, Special Publications, **300**: 61-89.

Burek, C.V. (2008). "History of RIGS in Wales: an example of successful cooperation for geoconservation." Burek, C.V. and Prosser, C.D. (eds.) The History of Geoconservation, Geological Society of London, Special Publications, **300**: 147-171.

Burek, C.V. and Prosser (eds.) (2008) The History of Geoconservation, Geological Society, London, Special Publications **300**, 312pp.

Burek C.V. and Hope M, (2010). "The use of town trails in raising awareness of urban geodiversity", in Engineering Geology for Tomorrow's Cities, Engineering Geology Special Publication, **22**.

Burek, C.V., (2011), Geovolunteers, The unpaid force that fuels Britain's geoconservation programme, Earth Heritage**,** **35**, 8-9.

Burek, C.V. (2012). "The Role of LGAPs (Local Geodiversity Action Plans) and Welsh RIGS as Local Drivers for Geoconservation within Geotourism in Wales". **Geoheritage**, **4**, 45-63

Burek, C.V., Ellis, N., Evans, D.H, Hart, M.B. and Larwood J (2013). "Marine Geoconservation in the United Kingdom" Proceedings of the Geologists' Association **124**(4): 581-592.

Burek, C.V., (2017). "Much to learn from dual geopark conferences", Earth Heritage, **47**, 5.

Calner, M., O. Lehnert and J. Nolvak (2010). "Palaeokarst evidence for widespread regression and subaerial exposure in the middle Katian (Upper Ordovician) of Baltoscandia: Significance for global climate." Palaeogeography, Palaeoclimatology, Palaeoecology **296(3-4)**: 235-247.

Calner, M., P. Ahlberg, O. Lehnart, and M. Erlstrom, (eds.), (2013), "The Lower Palaeozoic of Southern Sweden and the Oslo Region, Norway, Field Guide for the 3rd Annual Meeting of the IGCP Project 591", Geological Survey of Sweden.

Carter, R.M., S.T.Abbott, C.S.Fulthorpe, D.W.Haywick and R.A. Henderson (1991). "Application of global sea-level and sequence-stratigraphic models in southern hemisphere Neogene strata". In: Macdonald, D.I.M. (ed.), Sedimentation, Tectonics and Eustasy: Sea-Level Changes at Active Margins. International Association of Sedimentologists, Special Publication 12, 41–65.

Challands, T. J. (2008). Geosphere and Biosphere dynamics during Late Ordovician climate change. Department of Earth Sciences. Durham, Durham University. PhD.

Challands, T.J., H.A. Armstrong, D.P Maloney, J.R Davies, D. Wilson, and A. Owen, (2009). "Organic-carbon deposition and coastal upwelling at mid-latitude during the Upper Ordovician (Late Katian): A case study from the Welsh Basin, UK." Palaeogeography, Palaeoclimatology, Palaeoecology **273**(3-4): 395-410.

Chamberlain, C. K. 1971. "Morphology and ethology of trace fossils from the Ouachita Mountains, Southeast Oklahoma". Journal of Paleontology, **45**: 212–246.

Chen, X., J. Rong, J. Fan, R. Zhan, C.E. Mitchell, D.A.T. Harper, M.J. Melchin, P. Peng, S.C. Finney, and Wang, X. (2006). "The Global Boundary Stratotype Section and Point

(GSSP) for the base of the Hirnantian Stage (the uppermost of the Ordovician System)." Episodes **29**(3): 183-196.

Cherns, L. and J. R. Wheeley (2007). "A pre-Hirnantian (Late Ordovician) interval of global cooling - The Boda event re-assessed." Palaeogeography, Palaeoclimatology, Palaeoecology **251**(3-4): 449-460.

Cherns, L. and J.R Wheeley (2009). "Early Palaeozoic cooling events: peri-Gondwana and beyond" in Bassett M.G. (Ed.) Early Palaeozoic peri-Gondwana terranes: new

insights from tectonics and biogeography, Geological Society of London, Special Publications, **325**, 257-278.

Clark, J.W. and T.M. Hughes (1890). The Life and Letters of the Reverend Adam Sedgwick. Cambridge, Cambridge University Press.

Cocks, L. R. M. and R. A. Cooper (2004). "Late Ordovician (Hirnantian) shelly fossils from New Zealand and their significance." New Zealand Journal of Geology and Geophysics **47**(1): 71 - 80.

Cocks, L. R. M. and R. Fortey (1982). "Faunal evidence for oceanic separations in the Palaeozoic of Britain." Journal of the Geological Society **139:** 465-478.

Cocks, L. R. M. and R. A. Fortey (1997). "A new Hirnantia fauna from Thailand and the biogeography of the latest Ordovician of south-east Asia." Geobios **30**(Supplement 1): 117-126.

Cohen, K.M., Finney, S.C., Gibbard, P.L. and Fan, J.-X., 2013, The ICS International Chronostratigraphic Chart, Episodes, v. 36, no. 3, pp. 199-204.

Crimes, T. P. (1970). "The significance of trace fossils in sedimentology, stratigraphy and palaeoecology with examples from Lower Palaeozoic strata". in Trace Fossils. T. P. Crimes and J. C. Harper. Liverpool, Seel House Press: 101-126.

Crimes, T. P. and J. Crossley (1991). "A diverse ichnofauna from Silurian flysch of the Aberystwyth Grits Formation, Wales." Geological Journal **26**: 27-64.

Crimes, T. P. and J. C. Harper (1970). Trace Fossils, Liverpool, Seel House Press.

Dali, S. (1961). Quoted in "Illustrated Field Guide to the Geology of Cap de Creuss". Barcelona, Universitat autonoma de Barcelona.

Dattilo, B. F. (1996). "A quantitative paleoecological approach to high-resolution cyclic and event stratigraphy: the Upper Ordovician Miamitown Shale in the type Cincinnatian." Lethaia **29**(1): 21-36.

Davies, J. R., T. H. Sheppard, R.A Waters and D. Wilson (2006). Geology of the Llangranog district. Sheet Explanation of the British Geological Survey Sheet 194 (England and Wales), Nottingham, NERC.

Davies J.R, R. A. Waters, J.A. Zalasiewicz, S. G. Molyneux, T. R. A. Vandenbroucke and M. Williams (2009). "A revised sedimentary and biostratigraphical architecture for the Type Llandovery and Garth areas, Central Wales: a field guide". Open Report. Nottingham, British Geological Survey: **40**.

Davies, J.R., R. A. Waters, M. Williams, D. Wilson, D. I. Schofield and J. A. Zalasiewicz (2009) "Sedimentary and faunal events revealed by a revised correlation of post-glacial

Hirnantian (Late Ordovician) strata in the Welsh Basin, UK." Geological Journal **44**: 322-340.

Delabroye, A. and M. Vecoli (2010). "The end-Ordovician glaciation and the Hirnantian Stage: A global review and questions about Late Ordovician event stratigraphy." Earth-Science Reviews **98**(3-4): 269-282.

Donovan, S.K. and A.D Wright (1995). “Pelmatozoan (crinoid?) columnals from the Hirnantian (Ordovician, Ashgill) of Keisley, Cumbria”. Proceedings of the Yorkshire Geological Society, **50**.

Droser, M. L. and D. J. Bottjer (1986). "A semi-quantitative field classification of ichnofabric." Journal of Sedimentary Petrology **56**: 558-559.

Droser, M. L. and D. J. Bottjer (1989). "Ordovician increase in extent and depth of bioturbation: Implications for understanding early Paleozoic ecospace utilization." Geology **17**(9): 850-852.

Dunham, J. B. and E. R. Olson (1980). Shallow subsurface dolomitization of subtidally deposited carbonate sediments in the Hanson Creek Formation (Ordovician-Silurian) of Central Nevada. Concepts and Models of Dolomitization. In D. H. Zenger, J. B. Dunham and R. L. Ethington. Tulsa, Oklahoma, Society of Economic Paleontologists and Mineralogists. **28.**

EGF (2014). Geodiversity Charter for England. London, English Geodiversity Forum: 24pp.

Ehrenberg, K. (1944). "Erganzende Bemerkungen aus dem seinerzeit aus dem Miozan (Burdigal) von Burgschleinitz bei schriebenen Gangkernan und Bauten dekapoder Krebse" Palaont. Zeitschr. **23**: 354-359.

Elles, G. L. (1909). "The relation of the Ordovician and Silurian Rocks of Conway, North Wales." Quarterly Journal of the Geological Society of London **65**: 169-194.

Elles, G. L. (1922). "The Bala Country: its structure and rock-succession." Quarterly Journal of the Geological Society of London **78**: 132-175.

Elles, G. L. (1939). "The stratigraphy and faunal succession in the Ordovician rocks of the Builth - Llandrindod inlier, Radnorshire." Quarterly Journal of the Geological Society of London **380**: 383-445.

Elles, G. L. and E. M. R. Wood (1918). Monograph of British Graptolites, Palæontographical Society.

Elles, G. L., Shakespear, E. M. R. W., in Lapworth, C. (1901). A monograph of British graptolites. London: Printed for the Palæontographical Society.

Ellis, N. (2011). "The Geological Conservation Review (GCR) in Great Britain—Rationale and methods." Proceedings of the Geologists' Association **122**(3): 353-362.

Emmons, E. (1844). The Taconic System; based on observations in New York, Massachusetts, Maine, Vermont and Rhode Island. Albany, New York, Caroll & Cook.

Erikstad, L. (2013). "Geoheritage and geodiversity management - the questions for tomorrow." Proceedings of the Geologists' Association **124**(4): 713-719.

Fan, J., P. Peng and M. Melchin (2009). "Carbon isotopes and event stratigraphy near the Ordovician-Silurian boundary, Yichang, South China." Palaeogeography, Palaeoclimatology, Palaeoecology **276**(1-4): 160-169.

Farrow, G. E. (1990). Depth from trace and body fossils. Palaeobiology: a synthesis. D. E. G. Briggs and P. R. Crowther, Blackwell Science: 411-416.

Finlay, A. J., D. Selby, and D.R. Gröcke (2010). "Tracking the Hirnantian glaciation using Os isotopes." Earth and Planetary Science Letters **293**(3-4): 339-348.

Finnegan, S., K. Bergmann, J.M. Eiler, D.S.Jones, D.A. Fike, I. Eisenman, N.C. Hughes, A.K. Tripati and W.W. Fischer (2011). "The Magnitude and Duration of Late Ordovician–Early Silurian Glaciation." Science **331**(6019): 903-906.

Finnegan, S., N. A. Heim, S.E. Peters and W.W. Fischer (2012). "Climate change and the selective signature of the Late Ordovician mass extinction." Proceedings of the National Academy of Sciences **109**(18): 6829-6834.

Finney, S.C., W.B.N. Berry, J.D. Cooper, R.L. Ripperdan, W.C. Sweet, S.R. Jacobson, A. Soufinae, A. Achab, and P.J. Noble, (1999). "Late Ordovician mass extinction: A new perspective from stratigraphic sections in central Nevada." Geology **27**: 215-218.

Fitches, W. F. and N. Woodcock (1987). Sedimentation and Tectonics in the Welsh Basin, Aberystwyth, Geological Journal, **21**(S1).

Fortey, R. A., D. A. T. Harper, J. K. Ingham, A. W. Owen, A. W. A. Rushton and N. P. Woodcock, (2000). A Revised Correlation of Ordovician Rocks in the British Isles. London, Geological Society of London.

Frakes L.A., J.E.Francis and J.I. Syktus (1992). "Climate Modes of the Phanerozoic - the history of the earth's climate over the last 600 million years". Cambridge University Press.

Fritsch, A. (1908). "Problematica Silurica". Systeme Silurien du centre de la Boheme. J. Barrende. Prague: 28pp.

Geike, A. (1875). Life of Sir Roderick I Murchison. London, John Murray.

Ghavidel-syooki, M., J. J. Álvaro, L.V. Popov and A. Suyakova (2011). "Stratigraphic evidence for the Hirnantian (latest Ordovician) glaciation in the Zagros Mountains, Iran." Palaeogeography, Palaeoclimatology, Palaeoecology **307**(1-4): 1-16.

Ghienne, J.-F. (2003). "Late Ordovician sedimentary environments, glacial cycles, and post-glacial transgression in the Taoudeni Basin, West Africa." Palaeogeography, Palaeoclimatology, Palaeoecology **189**(3-4): 117-145.

Goldring, R. (1995). Organisms and the substrate; response and effect. Marine Palaeoenvironmental Analysis from Fossils. W. J. Bosence and P. A. Allinson. Geological Society of London: 151-180.

Goldring, R., Taylor, A.M. and Hughes, G.W. "The application of ichnofabrics towards bridging the dichotomy between siliciclastic and carbonate shelf facies: examples from the Upper Jurassic Fulmar Formation (UK) and the Jubaila Formation (Saudi Arabia)." Proceedings of the Geologists' Association **116**(3–4): 235-249.

Gotzinger, G. and H. Becker (1932). "Zur geoloischen Gliederung des Winerwaldflysches (Neue Fossilfunde)." Geol. Bundesanst. 82: 343-396.

Gordon J., A.J. Brooks, P. D. Chaniotis, B. D. James, N. H. Kenyon, A. B. Leslie, D. Long, and A. F. Rennie (2016) "Progress in marine geoconservation in Scotland's seas: assessment of key interests and their contribution to Marine Protected Area network planning" Proceedings of the Geologists' Association **127**: 716–737

Gould, S. J. (1989). *Wonderful Life*, Norton and Company.

Gould. S. J. (1999) *Rocks of Ages: Science and Religion in the Fullness of Life,* Ballantine Books, NewYork.

Gray, M. (2005). Geodiversity and Geoconservation: What, why and how? Geodiversity and Geoconservation. V. L. Santucci, The George Wright Forum. **22:** 4-12.

Groom, T. (1902). "The sequence of the Cambrian and associated beds of the Malvern Hills." Quarterly Journal of the Geological Society **58**: 89-149.

Hall, J. (1852). "Palaeontology of New York", **2**, State of New York; 362pp.

Hallam, A. (1988). Great Geological Controversies. Oxford, OUP.

Hallam, A. and P. B. Wignall (1999). "Mass extinctions and sea-level changes." Earth-Science Reviews **48**(4): 217-250.

Hambrey, M. J. (1985). "The late Ordovician—Early Silurian glacial period." Palaeogeography, Palaeoclimatology, Palaeoecology **51**(1-4): 273-289.

Hannigan, R., M. E. Brookfield, and A. Basu (2010). "A detailed 87SR/86SR isotopic curve for the mid-Cincinnatian (Upper Katian-Lower Hirnantian, Upper Ordovician), NE North American Shelf (Ontario, Canada) transition to the Hirnantian glaciation." Chemical Geology **277**(3-4): 336-344.

Hantzschel, W. (1975). "Trace Fossils and Problematica". Kansas, Treatise on Paleontology Part W, The Geological Society of America.

Heiland, J. (2014). pers.comm. "Trace fossil recovered from Ffestiniog Flags, Porthmadoc By-Pass". K. H. Nicholls.

Herringshaw L.G.and Davies N.S. (2008) Bioturbation levels during the end-Ordovician extinction event: a case study of shallow marine strata from the Welsh Basin. Aquatic Biology **2**:279–287

Hofmann, R., L. A. Buatois, R.B. MacNaughton and M.G.Mángano (2015). "Loss of the sedimentary mixed layer as a result of the end-Permian extinction." Palaeogeography, Palaeoclimatology, Palaeoecology **428**: 1-11.

Holmden, C., C.E. Mitchell, D.F. LaPorte, W.P. Patterson, M.J. Melchin and S.C. Finney (2013). "Nd isotope records of late Ordovician sea-level change—Implications for glaciation frequency and global stratigraphic correlation." Palaeogeography, Palaeoclimatology, Palaeoecology **386**(0): 131-144.

Holmden, C., K. Panchuk, and Finney S. (2012). "Tightly coupled records of Ca and C isotope changes during the Hirnantian glaciation event in an epeiric sea setting." Geochimica et Cosmochimica Acta **98**(0): 94-106.

Howells, M. F. (2007). Wales, British Geological Survey.

ICZN (2012). International Code of Zoological Nomenclature. International Commission on Zoological Nomenclature.

Jia-Yu, R., C. Xu, and D.A.T. Harper (2002). "The latest Ordovician Hirnantia Fauna (Brachiopoda) in time and space." Lethaia **35**(3): 231-249.

Jin, J., D.A.T Harper, J.A. Rasmussen, P.M. Sheehan, (2012). "Late Ordovician massive-bedded Thalassinoides ichnofacies along the palaeoequator of Laurentia." Palaeogeography, Palaeoclimatology, Palaeoecology 367-368: 73-88.

Jones, D.S., R.C. Creel, and, Rios B. (2016). "Carbon isotope stratigraphy and correlation of depositional sequences in the Upper Ordovician Ely Springs Dolostone, eastern Great Basin, USA." Palaeogeography, Palaeoclimatology, Palaeoecology **458**: 85-101.

Jones, O. T. (1912). "The geological structure of Central Wales and the adjoining regions" Quarterly Journal of the Geological Society **68**: 328-344.

Jones, O. T. (1925). "The geology of the Llandovery District (Part 1): The Southern Area." Quarterly Journal of the Geological Society of London **81**: 344-388.

Jones, O. T. (1938). "On the evolution of a geosyncline." Quarterly Journal of the Geological Society of London **94.**

Jones, O. T. (1949). "The geology of the Llandovery District, Part 2, The Northern Area " Quarterly Journal of the Geological Society of London **105**: 43-64.

Jonin, M. (2008). “Geodiversite en Bretagne – un patrimoine remarquable” (Geodiversity in Brittany – a remarkable heritage), Societe geologique et mineralogique de Bretagne

Kaljo, D., L. Hints, T. Martma, and Nõlvak , J. (2001). "Carbon isotope stratigraphy in the latest Ordovician of Estonia." Chemical Geology **175**(1-2): 49-59.

Kelly, S. R. A. (1990). Trace Fossils in Palaeobiology: a synthesis. Eds. D. E. G. Briggs and P. R. Crowther, Blackwell Science: 423-424.

Ksiazkiewicz, M. (1968). "On some problematic organic traces from the flysch of the Polish Carapthians (Part III)." Annals of the Geological Society of Poland **38**: 3-17.

LaPorte, D.F., C.Holmden, W.P.Patterson, J.D.Loxton, M.J. Melchin and C.E.Mitchell, (2009). "Local and global perspectives on carbon and nitrogen cycling during the Hirnantian glaciation." Palaeogeography, Palaeoclimatology, Palaeoecology **276**(1-4): 182-195.

Lapworth, C. (1879). "On the tripartite classification of the Lower Palaeozoic rocks." Geological Magazine **2**(6): 1-15.

Larwood, J. G., T. Badman and P.J. McGeever (2013). "The Progress and Future of Geoconservation at a global level." Proceedings of the Geologists' Association **124**(4): 720-730.

Lehnert, O., P. Mannik, J. Nõlvak, B. Kröger, M. Joachimski, M. Calner, and H. Bauert (2016). Glacioeustatic karst development in the Late Ordovician of Baltica. The Early to Mid Palaeozoic Revolution. Ghent, International Geoscience Program Project 591. **Abstracts.**

Leng, M. J. and R. Cave (1993). "The Machynlleth and Llanidloes Areas". Geological Excursions in Wales. N. H. Woodcock and M. G. Bassett. Cardiff, National Museum of Wales: pp129-154.

Leszczynski, S. (1991) "Oxygen-related controls on pre-depositional ichnofacies in turbidites, Guipuzcoan Flysch (Albian- Lower Eocene), northern Spain". Palaios **6**

Lind Hendriks, E.M. (1926) The Bala-Silurian succession in the Llangranog District (South Cardiganshire)" Geological Magazine 63 (3): 121-139.

Loi, A., J.-F. Ghienne, M.P. Dabard, F. Paris, A. Botquelen, N. Christ, Z. Elaouad-Debbaj, A.Gorini, M. Vidal, B.Videt and J. Destombes (2010). "The Late Ordovician glacio-eustatic record from a high-latitude storm-dominated shelf succession: The Bou Ingarf section (Anti-Atlas, Southern Morocco)." Palaeogeography, Palaeoclimatology, Palaeoecology **296**(3-4): 332-358.

Long, D. G. F. (1993). "Oxygen and carbon isotopes and event stratigraphy near the Ordovician--Silurian boundary, Anticosti Island Quebec." Palaeogeography, Palaeoclimatology, Palaeoecology **104**(1-4): 49-59.

Lucretius (1920). On the Nature of Things. R. C. Trevelyan. London, Allen and Unwin.

Ludt, W.B. and L. A. Rocha (2015) "Shifting seas: the impacts of Pleistocene sea-level fluctuations on the evolution of tropical marine taxa" Journal of Biogeography, **42**, 25–38

MacLeay, W. S. (1839). "Notes on the Annelida". The Silurian System. R. I. Murchison. London, John Murray.

Magor, P. M. (2012). Specimens held at Sedgwick Museum. KHN. unpublished personal communication.

Mapstone, N. B. and D. McIlroy (2006). "Ediacaran fossil preservation: Taphonomy and diagenesis of a discoid biota from the Amadeus Basin, central Australia." Precambrian Research **149**(3-4): 126-148.

Marshall, J. D., P. J. Brenchley, P. Mason, G. A. Wolff, R. A. Astini, L. Hints and T. Meidla (1997). "Global carbon isotopic events associated with mass extinction and glaciation in the late Ordovician." Palaeogeography, Palaeoclimatology, Palaeoecology **132**(1-4): 195-210.

McCall, G. J. H. (2006). "The Vendian (Ediacaran) in the geological record: Enigmas in geology's prelude to the Cambrian explosion." Earth-Science Reviews **77**(1-3): 1-229.

McCann, T. (1990). "Distribution of Ordovician-Silurian ichnofossil assemblages in Wales - implications for Phanerozoic ichnofaunas." Lethaia 23(3): 243-255.

McCann, T. (1993). "A Nereites ichnofacies from the Ordovician□Silurian Welsh Basin." Ichnos 3(1): 39-56.

McElvey, V. E. (1972). "Mineral Resource Estimates and Public Policy." American Scientist **60**(1): 32-40.

McGhee, G.R. Jr., P.M. Sheehan, D.J Bottjer and M.L Droser (2004). "Ecological ranking of Phanerozoic biodiversity crises: ecological and taxonomic severities are decoupled." Palaeogeography, Palaeoclimatology, Palaeoecology **211**: 289-297.

McKerrow, W.S., Mac Niocaill, C., & Dewey, J.F. (2000). "The Caledonian Orogeny redefined". Journal of the Geological Society, London, **157**, 1149-1154.

McIlroy, D. and J. Horak (2006). "Neoproterozoic; the late Precambrian terranes that formed Eastern Avalonia", in Brenchley, P. and Rawson P. (Eds.) The Geology of England and Wales, 2nd Edition, Geological Society, London: 9-24

Melchin, M. J. and C. Holmden (2006). "Carbon isotope chemostratigraphy in Arctic Canada: Sea-level forcing of carbonate platform weathering and implications for Hirnantian global correlation." Palaeogeography, Palaeoclimatology, Palaeoecology **234**(2-4): 186-200.

Menon, L.R, D. McIlroy and M Brasier (2016). "'Intrites' from the Ediacaran Longmyndian Supergroup, UK: a new form of microbially-induced sedimentary structure in Brasier, A. T., D.McIlroy, & N. McLoughlin, N. (eds) Earth System Evolution and Early Life: a Celebration of the Work of Martin Brasier. Geological Society, London, Special Publications, **448**

Mergl, M. (2011). "Earliest occurrence of the *Hirnantia* Fauna in the Prague Basin (Czech Republic)." Bulletin of Geosciences **86**(1): 63-70.

Merriman, R J. 2006. "Clay mineral assemblages in British Lower Palaeozoic mudrocks". Clay Minerals, **41**, 473–512.

Mignon P. and E. Pijet-Mignon (2016) "Geoconservation and tourism at geothermal sites – lessons learnt from the Taupo Volcanic Zone, New Zealand" Proceedings of the Geologists' Association **127**: 413–421

Monro, S. (2011). Raising public awareness of geodiversity and geoconservation. Geoconservation for Science and Society: An Agenda for the 21st Century. Proceedings of the Geologists' Association **122**(3)

Morris, J. L., V. P. Wright, et al. (2012). "Siluro-Devonian landscapes of southern Britain; the stability and nature of early vascular plant habitats." Journal of the Geological Society **169**(2).

Murchison, R. I. (1839). "The Silurian System, founded on Geological Researches in the counties of Salop, Hereford, Radnor, Montgomery, Carmarthen, Brecon, Pembroke, Monmouth, Gloucester, Worcester and Stafford with descriptions of the Coal-fields and overlying formations". London, John Murray.

Neches, I.-M. (2016) "Geodiversity beyond material evidence: a Geosite Type based interpretation of geological heritage" Proceedings of the Geologists' Association **127**: 78–89

Nicholls, K.H. (2011). "Climate amelioration in the latest Ordovician - Did weathering of exposed carbonate shelf bring the Hirnantian Glacial Episode to a close?" Poster Presentation at Life and the Planet, Geological Society of London.

Nicholls, K. H. and C. V. Burek (2015). "Geoconservation and geodiversity: What? Who? Where? - and why should I care?" Geotechnical Engineering for Infrastructure and Development, Edinburgh, Thomas Telford.

Nicholson (1873). "Contributions to the study of the errant annelides of the older Palaeozoic rocks." Royal Society of London, Proceedings **21**: 288-290.

Orr, P. (2001). "Colonization of the deep-marine environment during the early Phanerozoic: the ichnofaunal record " Geological Journal **36**: 265-278.

Osgood, R. (1970). "Trace Fossils of the Cincinatti area." Palaeontographica Americana **VI**(41): 280-444.

Packard, A. S. (1900). "On supposed merastomatous and other Paleozoic arthropod trails with notes on those of *Limulus*." American Academy of Arts and Science, Proceedings **36:** 61-71.

Pearson. N.J., M. G. Mángano, L. A. Buatois, S. Casadío and M.R. Raising (2012). "Ichnology, sedimentology, and sequence stratigraphy of outer-estuarine and coastal-plain deposits: Implications for the distinction between allogenic and autogenic expressions of the *Glossifungites* Ichnofacies." Palaeogeography, Palaeoclimatology, Palaeoecology **333–33**4(0): 192-217.

Pemberton, J. W., R. W. Frey, and D.A. Saunders (1990). "Trace Fossils" in Palaeobiology: A synthesis. Eds D. E. G. Briggs and P. R. Crowther, Blackwell Science: 355-361.

Pickerill, R. K. (1977). "Trace fossils from the Upper Ordovician (Caradoc) of the Berwyn Hill, Central Wales." Geological Journal **12**.

Pimm, S.L. and C.N. Jenkins (2010). "Extinctions and the practice of preventing them" in Sodhi, N.S. and Ehrlich, P.R. (Eds.): Conservation Biology for All: 181-198. Oxford University Press.

Powell, J., G. Nash, et al. (2013). "Geoexposures: Documenting temporary geological exposures in Great Britain through a citizen-science web site." Proceedings of the Geologists' Association **124**(4): 638-647.

Price D (1980) “A revised age and correlation for the topmost Sholeshook Limestone Formation (Ashgill) of South Wales” Geological Magazine **117**(05).

Prosser, C. D., D. R. Bridgland, et al. (2011). "Geoconservation for science and society: challenges and opportunities." Proceedings of the Geologists' Association **122**(3): 337-342.

Prosser, C. D. (2013). "Our rich and varied Geoconservation Portfolio: the Foundation for the Future." Proceedings of the Geologists' Association **124**(4): 568-580.

Ramsay, A. C. (1866). The Geology of North Wales. London, Longmans, Green, Reader and Dyer.

Rasmussen, C. M. Ø. and D. A. T. Harper (2011). "Did the amalgamation of continents drive the end Ordovician mass extinctions?" Palaeogeography, Palaeoclimatology, Palaeoecology **311**(1–2): 48-62.

Raup, D. M. and J. J. J. Sepkoski (1982). "Mass extinction in the marine fossil record." Science **215**: 1501-1503.

Roberts, R. (2013). List of current Welsh RIGS sites. Mold, Natural Resources Wales.

Robertson, D. B. R., P. J. Brenchley, and A.W. Owen (1991). "Ecological disruption close to the Ordovician-Silurian boundary." Historical Biology: An International Journal of Paleobiology **5**(2): 131 - 144.

Rodríguez-Tovar F.J., A. Uchman, A. Payros, X. Orue-Etxebarria, E Apellaniz and E. Molina. (2010) "Sea-level dynamics and palaeoecological factors affecting trace fossil distribution in Eocene turbiditic deposits (Gorrondatxe section, N Spain)." Palaeogeography, Palaeoclimatology, Palaeoecology **285** (1-2): 50-65.

Rong, J., M. J. Melchin, S. H. Williams, T. N. Koren and J. Verniers (2008). "Report of the restudy of the defined global stratotype of the base of the Silurian System." Episodes **31**(3): 315-318.

Ruban, D. (2012) "Geoconservation versus legislation and resources policy: New achievements, new questions — Comment on Cairncross (Resources Policy, 2011) The National Heritage Resource Act(1999): Can legislation protect South Africa's rare geoheritage resources?" Resources Policy **37**: 126–129

Ruppert, E. E. and R. D. Barnes (1994). Invertebrate Zoology, Saunders College Publishing.

Salter, J. W. (1866). The Geology of North Wales. Memoirs of the Geological Survey of Great Britain and the Museum of Practical Geology. A. C. Ramsay. London, Longmans, Green, Reader and Dyer. Appendix on the Fossils with Plates.

Schmitz, B. and S. M. Bergström (2007). "Chemostratigraphy in the Swedish Upper Ordovician: Regional significance of the Hirnantian δ13C excursion (HICE) in the Boda Limestone of the Siljan region." GFF **129**(2): 133 – 140.

Schofield, D. I., J. R. Davies, R. A. Waters, M. Williams and D. Wilson (2008). "A new Early Silurian turbidite system in Central Wales: insights into eustatic and tectonic controls on deposition in the southern Welsh Basin." Geological Magazine **146**: 121-132.

Scott, P. W. (2005). GeoValue: Valuing Geodiversity for Conservation - Development of the Geodiversity Profile. D. P. Roche. Exeter: 102pp.

Scrutton, C. T. (1990). "Reefs". Palaeobiology - A synthesis. D. E. G. Briggs and P. R. Crowther. Oxford, Blackwell Science Ltd: 52-56.

Sedgwick, A. in J.W. Salter (1873), "A Catalogue of the Collection of Cambrian and Silurian fossils contained in the Geological Museum at the University of Cambridge." Cambridge University Press.

Semple, J. T. (1965). "Upper Ordovician brachiopods from Poland and Britain." Acta Palaeontologica Polonica **X**(3): 93.

Seilacher, A. (1953). "Studien zur Palichnologie1. Uber die methoden der palichnologie." Neues Jahrbuch fur gelogie and palaeontologie 96: 421-452.

Seilacher, A. (1967). "Bathymetry of trace fossils." Marine Geology 5: 413-428.

Seilacher, A. (1970). "Cruziana stratigraphy of "non-fossiliferous" Palaeozoic sandstones". Trace Fossils. T. P. Crimes and J. C. Harper. Liverpool, Liverpool Geological Society. 3: 447-476.

Seilacher, A. (2007). “Trace Fossil Analysis”, Springer.

Seilacher, A., L. A. Buatois, and M. G. Mangano (2005). "Trace fossils in the Ediacaran-Cambrian transition: Behavioral diversification, ecological turnover and environmental shift." Palaeogeography, Palaeoclimatology, Palaeoecology **227**(4): 323-356.

Sepkoski, J. J. J. (1982). "Mass extinctions in the Phanerozoic marine fossil record." Paleobiology 7: 36-53.

Sepkoski, J. J. J. (1986). Phanerozoic overview of mass extinctions. Patterns and processes in the history of life. D. M. Raup and D. Jablonski. Berlin, Springer-Verlag: 277-295.

Servais, T., S. Clausen, T. Danelian, D.A.T. Harper, B. Kröger, B. Lefebvre, C. Monnet, A. Munnecke, E. Nardine, T. Vandenbroucke and J. Vannier (2011). "Cambrian Explosion and Ordovician Biodiversification, or Cambrian Biodiversification and Ordovician Explosion", 55th Palaeontological Association Annual Meeting. Newsletter of the Palaeontological Association. **78**.

Servais, T., D.A.T. Harper, A. Munnecke and P. Sheehan (2009). "Understanding the Great Ordovician Biodiversification Event (GOBE): Influences of paleogeography, paleoclimate, or paleoecology?" GSA Today **19**: 4-10.

Servais, T., A.W. Owen, D.A.T. Harper and A. Munnecke (2010). "The Great Ordovician Biodiversification Event (GOBE): The palaeoecological dimension." Palaeogeography, Palaeoclimatology, Palaeoecology **294**(3-4): 99-119.

SGF (2013). Scottish Geodiversity Charter. Edinburgh, Scottish Government: 16pp.

Sheehan, P. M. (2001). "The Late Ordovician Mass Extinction." Annual Review Earth and Planetary Science 29: 331-364.

Sheehan, P. M. and P. J. Coorough (1990). "Brachiopod zoogeography across the Ordovician-Silurian extinction event." Geological Society, London, Memoirs **12**(1): 181-187.

Simpson, S. (1956). "On the trace-fossil *Chondrites*." Quarterly Journal of the Geological Society of London **448**: 475-499.

Slack, R. (2000) Lead miners’ heyday: the great days of mining in Wirksworth and the Low Peak of Derbyshire. Peak District Mines Historical Society, 79pp.

Smith, M. E., B. S. Singer, et al. (2011). "A time like our own? Radioisotopic calibration of the Ordovician greenhouse to icehouse transition." Earth and Planetary Science Letters **311**(3-4): 364-374.

SNH (2008). Scottish Fossil Code. Edinburgh, Scottish Natural Heritage: 58pp.

von Sternberg, K. M. G. (1833). Versuch einer geognostisch-botanischen Darstellung der Flora der Vorwelt. Leipzig & Prague.

Strachan R.A., R.D., Nance, R. D. Dallmeyer, R.S. D'Lemos, J. B. Murphy and G.R.Watt (1996). "Late Precambrian tectonothermal evolution of the Malverns Complex" Journal of the Geological Society, London, **Vol. 153**, 1996, pp. 589-600

Sutton, M. D., D. E. G. Briggs, et al. (2012). "A Silurian armoured aplacophoran and implications for molluscan phylogeny.", Nature **490**(7418): 94-97.

SVP (2010). Standard Procedures for the Assessment and Mitigation of Adverse Impacts to Paleontological Resources, Impact Mitigation Guidelines Revision Committee: 11.

Temple, J. T. (1965). "Upper Ordovician Brachiopods from Poland and Britain." Acta Palaeontologica Polonica **X**(No. 3): 379-427.

Toghill, P. (1990) Geology in Shropshire, Swan Hill Press, Shrewsbury.

Trewin, N. H. (1994). "A draft system for the identification and description of arthropod trackways." Palaeontology **37**(4): 811-823.

Trythall, R. J. B. (1988). The Mid-Ordovician Oolitic Ironstones of North Wales, Luton College of Higher Education. D.Phil.

Twitchett, R. J. (2006). "The palaeoclimatology, palaeoecology and palaeoenvironmental analysis of mass extinction events." Palaeogeography, Palaeoclimatology, Palaeoecology **232**: 190-213.

Underwood, C., S. F., Crowley, J. D. Marshall and P. J. Brenchley (1997) "High-resolution carbon isotope stratigraphy of the basal Silurian Stratotype (Dob's Lin, Scotland) and its global correlation." Journal of the Geological Society of London **154**: 709-718.

Vandenbroucke, T. R. A. (2008). "An Upper Ordovician chitinozoan biozonation in British Avalonia (England and Wales)." Lethaia **41**(3): 275-294.

Vandenbroucke, T.R.A., J. Hennissen, J. Zalasiewicz, and J. Verniers, (2008). "New chitinozoans from the historical type area of the Hirnantian Stage and additional key sections in the Wye Valley, Wales, UK." Geological Journal **43**: 397-414.

Vandenbroucke, T. R. A., H. A. Armstrong, M.Williams, J. A. Zalasiewicz and K. Sabbe, (2010). "Polar front shift and atmospheric CO2 during the glacial maximum of the Early Paleozoic Icehouse." Proceedings of the National Academy of Sciences of the United

States of America. **107**(34): 14983-14986.

Verniers, J. and T. R. A. Vandenbroucke (2006). "Chitinozoan biostratigraphy in the Dob's Linn Ordovician-Silurian GSSP, Southern Uplands, Scotland." GFF 128(2): 195 - 202.

Villas, E., E. Vennin, J. J. Alvaro, W. Hammann, Z. A. Herreraand E.L. Piovano, (2002). "The late Ordovician carbonate sedimentation as a major triggering factor of the Hirnantian glaciation." Bulletin de la Societe Geologique de France **173**(6): 569-578.

Voora, V. A. and H. D. Venema (2008). "The Natural Capital Approach - A Concept Paper."

Wake, D.B. and V.T. Vrendenburg (2008). "Are we in the midst of the sixth mass extinction? A view from the world of amphibians." Proceedings of the National Academy of Sciences, **105**: Supplement 1.

Walcott, C. D. (1914). "Pre-Cambrian algal flora". Cambrian geology and paleontology III, Smithsonian Miscellaneous Collections. **64**, (2): 115-216.

Wang, L., M., Tian, X. Wen, L. Zhao, J. Song, M. Sun, H. Wang, Y. Lan Y and M. Sun (2014). "Geoconservation and geotourism in Arxan-Chaihe Volcano Area, Inner Mongolia, China" Quaternary International, **349**: 384-391

Williams, S. H. (1983). "The Ordovician-Silurian boundary graptolite fauna of Dob's Linn, Southern Scotland." Palaeontology 26(3): 605-639.

Williams-Ellis, C. (1971). *Architect Errant*. London, Constable and Company.

Wolfe, L. M. (1945*). Son of all the Wilderness - the Life of John Muir*. New York, Alfred A Knopf.

Wood, A. (2013). "Forward." Proceedings of the Geologists' Association **124**(4): 559-560

Wood, M. (2007). Developing a Methodology for Selecting Regionally Important Sites (RIGS) in Wales & A RIGS Survey of Anglesey & Gwynedd AWRG, Association of Welsh RIGS Groups. **2**.

Woodcock, N. (2000). "Introduction to the Silurian", in Palmer, D., Siveter, D.J., Lane, P., Woodcock, N. & Aldridge, R., British Silurian Stratigraphy, Geological Conservation Review Series, 19, Joint Nature Conservation Committee, Peterborough: 3-22.

Woodcock, N. and M. Bassett (1993). *Geological Excursions in Powys*. Cardiff, National Museum of Wales.

Wright, A. D. (1968). "A Westward Extension of the Upper Ashgillian Hirnantia Fauna." Lethaia **1**(4): 352-367.

Wright, V.P. and Cherns, L. (2016). "How far did feedback between biodiversity and early diagenesis affect the nature of the early Palaeozoic sea floors?" Palaeontology **59** (6): 753-765.

Xiaofeng, W. and C. Zhifang (1990). "Ordovician-Silurian Boundary Extinction and Its Relationship to Iridium and Carbon Isotope Anomalies." Acta Geologica Sinica - English Edition **3**(1): 81-92.

Xu, C. (1984). "Influence of the Late Ordovician glaciation on basin configuration of the Yangtze Platform in China." Lethaia **17**(1): 51-59.

Yan, D., D. Chen, Q. Wang and Z. Wang (2009). "Carbon and sulfur isotopic anomalies across the Ordovician-Silurian boundary on the Yangtze Platform, South China." Palaeogeography, Palaeoclimatology, Palaeoecology **274**(1-2): 32-39.

Zhan R., J. Liu, Y. Liang and G. Li (2011). "α- and β-diversity Change of Late Ordovician *Hirnantia* Fauna of Changning, Sichuan, Southwest China." Acta Geologica Sinica - English Edition **85**(2): 330-339.

Appendices

Appendix 1: **CD with Specimen Collection Database**

Bound in to inside of rear cover

Appendix 2: **XL spreadsheet summarising Treatise Part W (Haentzschel, 1975)**

Bound in to inside of rear cover

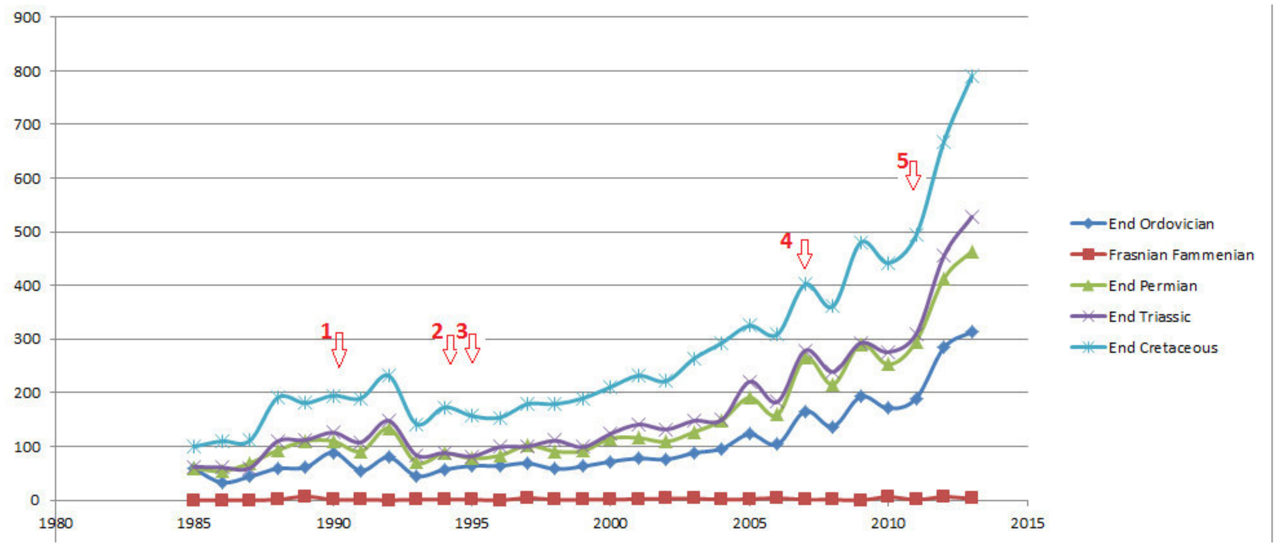
Appendix 3: Science Direct Research Searches

Science direct search

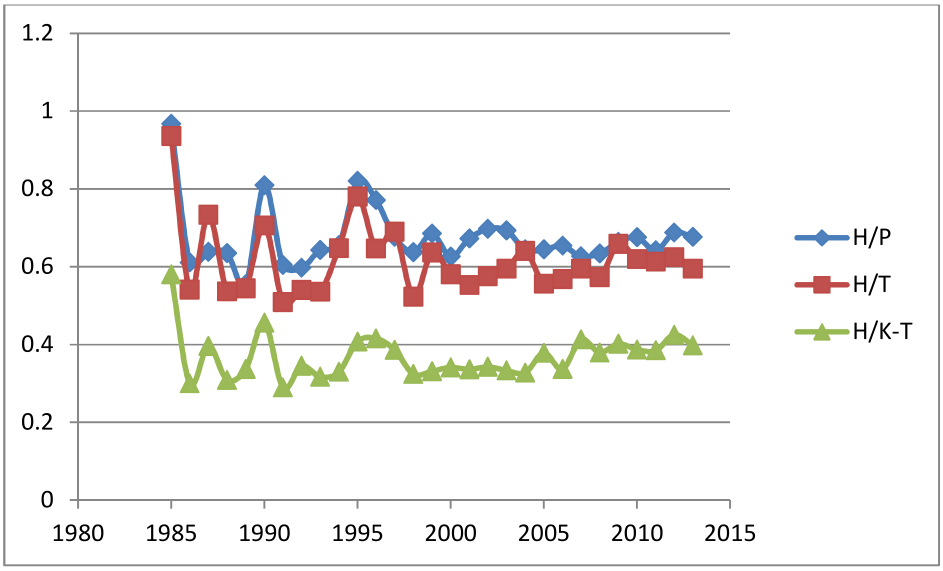
The table below illustrates the gross numeric results of a Science Direct search on the following terms (as at May 31st and June 1st 2014), covering the period 1985 to 2013.

- (Year), End Ordovician, trace fossils
- (Year), Frasnian Fammenian, trace fossils
- (Year), End Permian, trace fossils
- (Year), End Triassic, trace fossils
- (Year), End Cretaceous, trace fossils

Science Direct listings – 1995 to 2013, trace fossils and the "Big 5" Phanerozoic Mass Extinction Episodes					
Year	End Ordovician	Frasnian - Fammenian	End Permian	End Triassic	End Cretaceous
1985	58	0	60	62	100
1986	33	0	54	61	110
1987	44	0	69	60	111
1988	59	1	93	110	191
1989	61	7	110	112	181
1990	89	1	110	126	195
1991	55	1	91	108	190
1992	80	0	134	148	232
1993	45	1	70	84	142
1994	57	1	87	88	173
1995	64	1	78	82	157
1996	64	0	83	99	154
1997	69	4	102	100	179
1998	58	1	91	111	179
1999	63	1	92	99	190
2000	72	1	115	124	211
2001	78	2	116	141	232
2002	76	3	109	132	222
2003	88	3	127	148	264
2004	96	1	149	150	293
2005	123	2	191	221	325
2006	104	4	159	183	309
2007	166	1	265	279	402
2008	137	1	216	239	361
2009	193	0	291	293	480
2010	171	6	253	276	442
2011	190	1	296	310	494
2012	284	6	413	455	668
2013	314	3	464	528	790

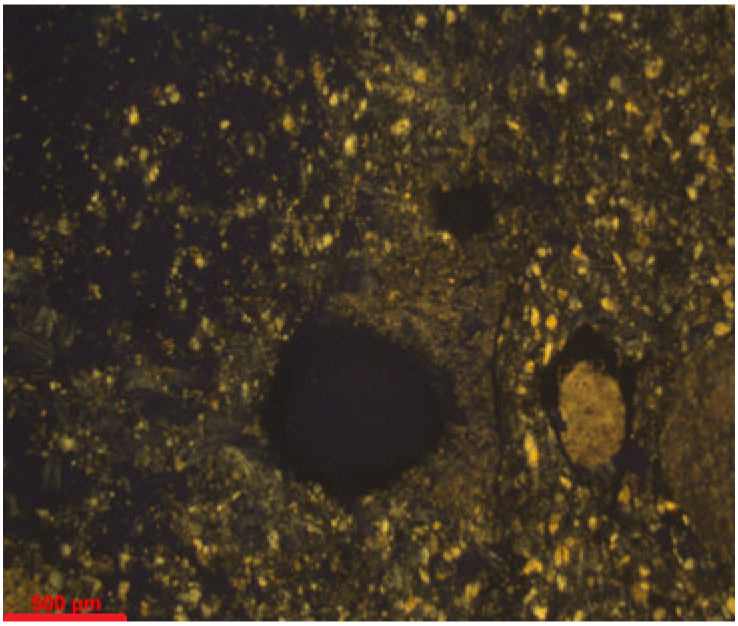


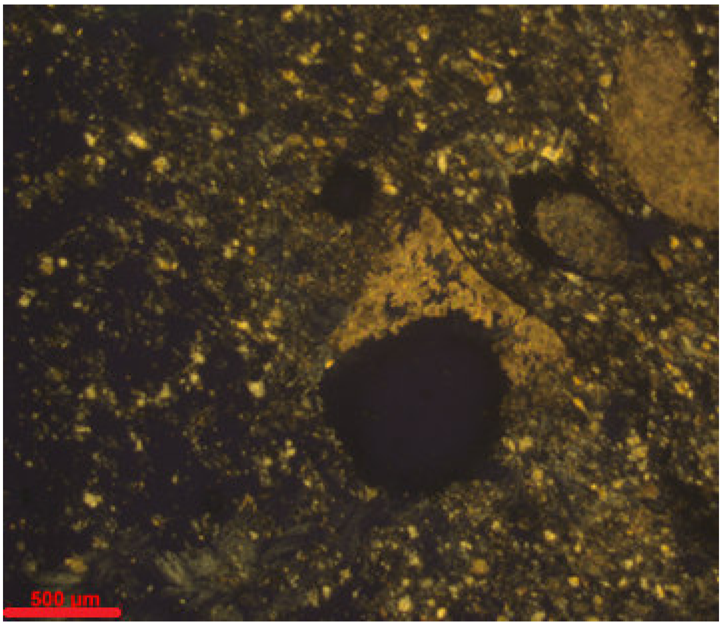
1 McCann, 1990; , Bromley, 1990; Briggs and Crowther,1990
2 McCann, 1993
3 GS SP #83
4 Seilacher, 2007
5 Buatois and Gabriela Mangano, 2011



This plot shows the comparison between the ratios of hits relating to studies involving the end Ordovician - Hirnantian (H) in comparison with the end Permian (P), end Triassic (T) and end Cretaceous (K-T) events.

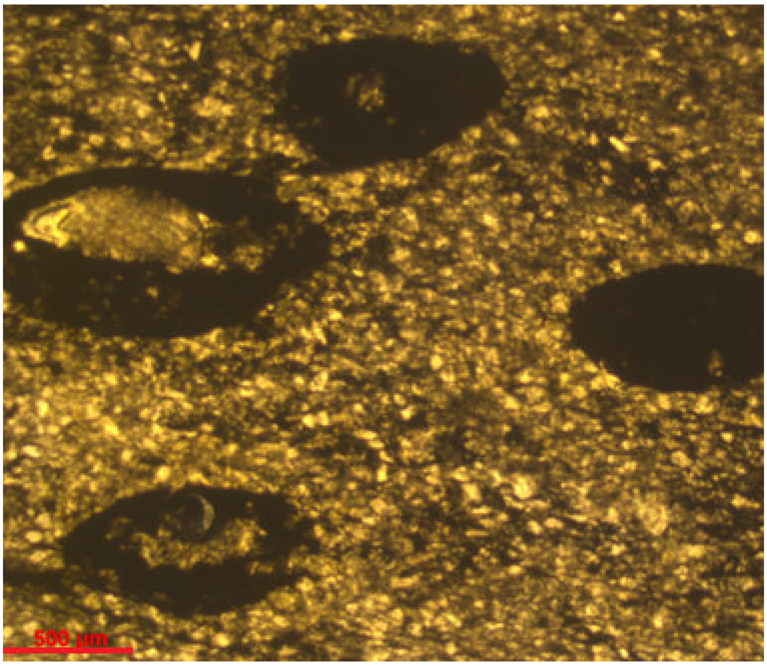
Appendix 4: Hirnant Limestone Microsope Thin Sections

a) 

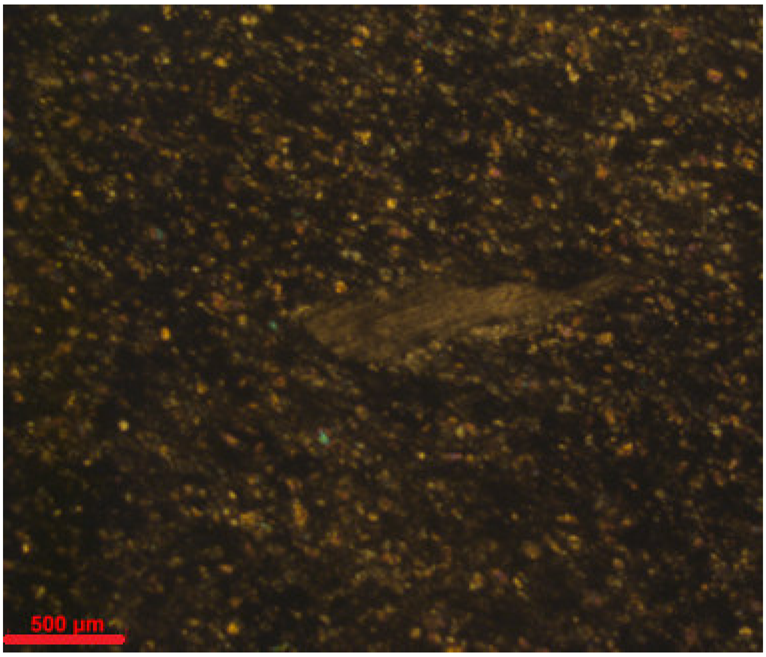
b) 

a) Groundmass of microcrystalline calcite with ooids and lithic clasts. Lithic clast of cryptocrystalline calcite with sub-circular ooid c. 600um diameter. Ooid to right of centre is elongate / elliptical with presumed calcite overgrowth with long axis orientated parallel to presumed bedding direction (sub-vertical as expressed in above image).

b) Same image as HL01-01 previously but with stage rotated approximately 45^0 anti-clockwise (both images 1) and 2) taken with crossed polars).



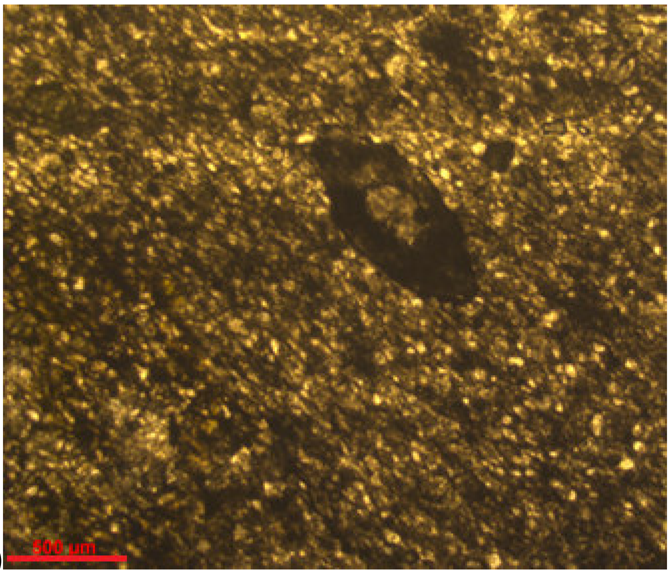
c)



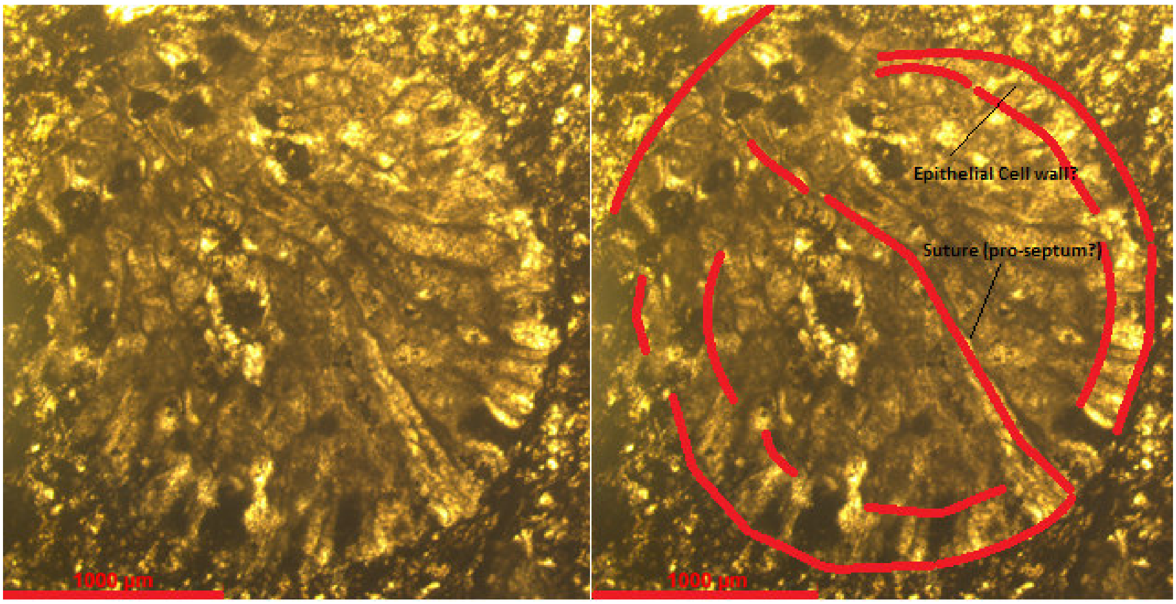
d)

c) Groundmass of microcrystalline calcite with four elongate ooids up to c. 1.25mm measured along the long axis c. 0.6mm diameter. Long axes are sub-parallel. Three of the ooids appear to be concentrically zoned. The fourth ooid – at the right of the field of view - appears to be lacking in any obvious internal structure. Plane polarized light.

d) Ground mass of micro-crystalline calcite with a single irregular lithic fragment, apparently composed of extremely finely laminated mudstone. Crossed polars.



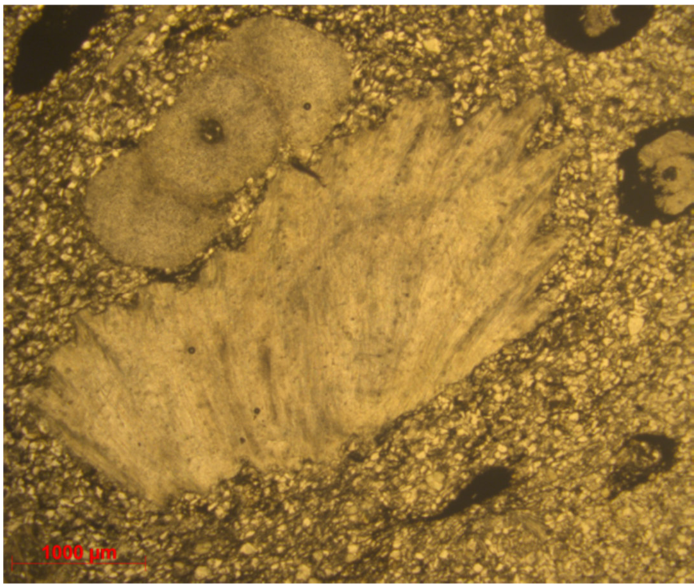
e)



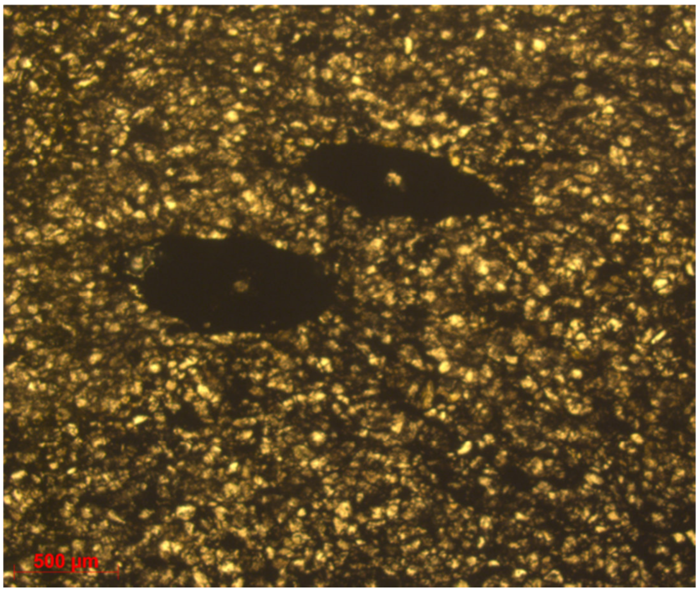
f)

e) A single highly elliptical ooid is centred within a groundmass of microcrystalline calcite. The ooid is concentrically zoned and appears to have grown around an original sub-elliptical calcite ooid. The long axis of the elliptical ooid is orientated parallel with a set of laminations orientated at 45^0 to the horizontal and thought to represent a developing cleavage plane associated with the growth of clay mineral laminae. The original bedding is thought to be represented by a band of pale colour near the top of the image. Plane polarised light.

f) Set within a fine grained calcite matrix this slide shows an ovoid or disc like structure of approximately 2.5mm diameter. This appears to be of organic origin with a suture (pro-septum?) and apparent epithelial cell wall evident .This is thought to be a bryozoan c.f. *Helapora fragilis* as described from coeval strata in Argentina by Halpern and Carrera (2014). Alternatively this may represent a calcareous alga. Plane polarised light.



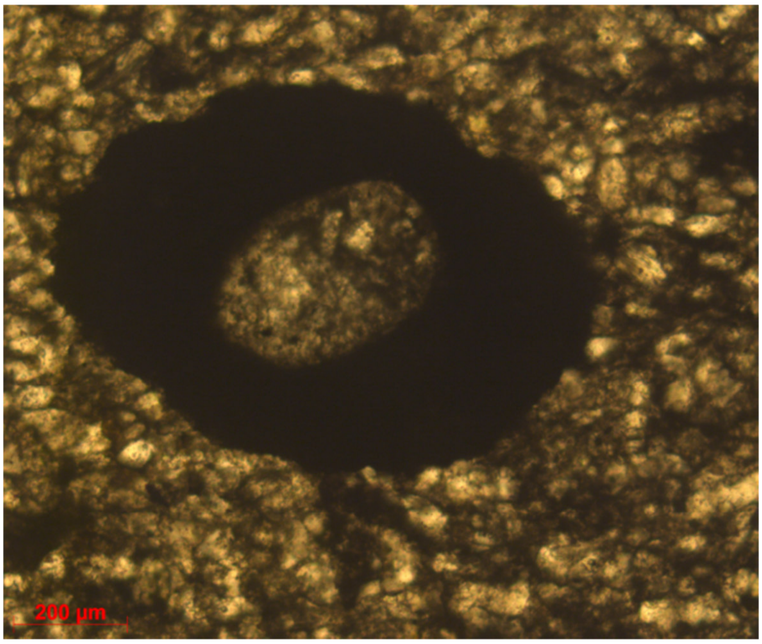
g)



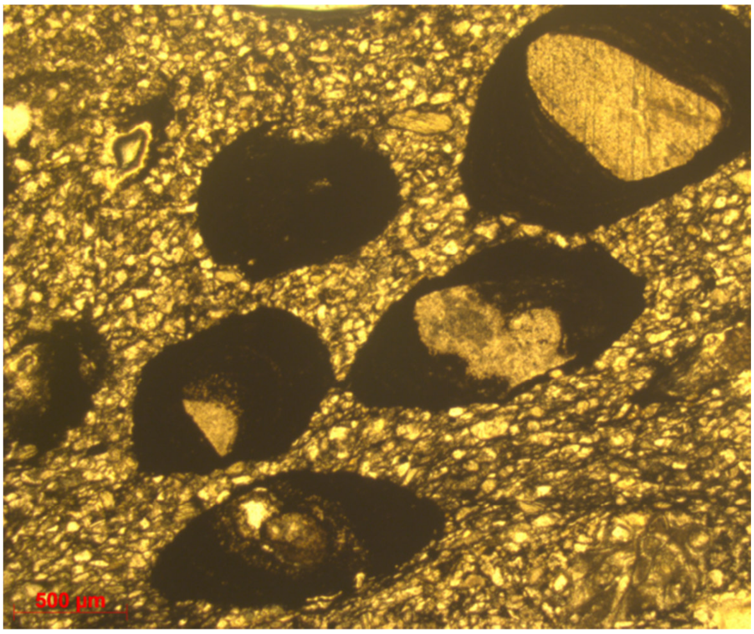
h)

g) A fine calcitic matrix includes a number of concentrically zoned ooids less than 1mm diameter (with discrete original seed lithic / mineral clasts apparent). One of the large ooids (toward the top left of the image shows the apparent fusing with two adjacent ooids of similar size and composition. The centre of the image is dominated however by a large and only partially abraded conodont element, tentatively assigned to the Laurentian Hirnantian species *Rhipognathus symmetricus*? Plane polarised light.

h) Two ovoid ooids slightly less than 1mm long up to 0.5mm diameter lie in a matrix of fine grained calcitic mud. The original lithic / mineral "seed" grains at the centre of each ooid are clearly visible. An apparent obliquity between developing cleavage (ooid long axis orientation) and original bedding (gently inclined upwards from left to right of field of view) is apparent. Crossed polars.



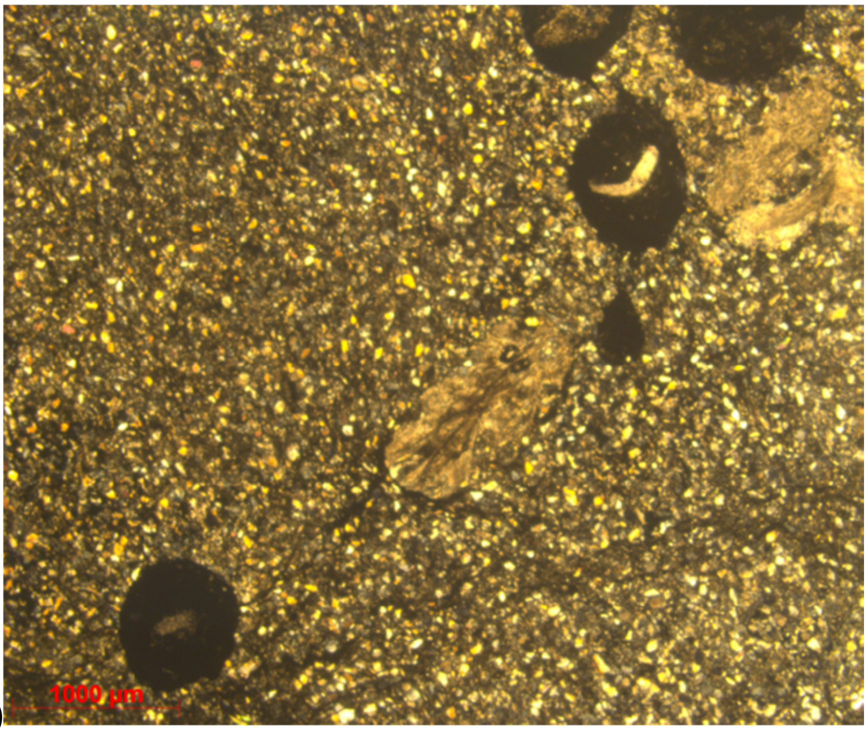
i)



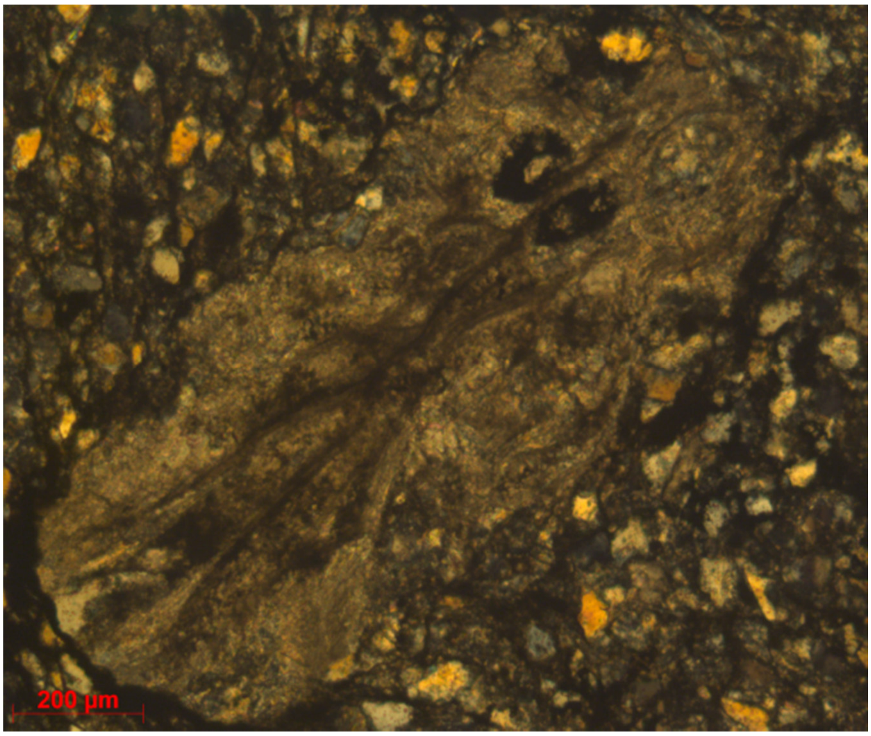
j)

i) Close up image of ooid of about 0.5mm diameter. Slightly irregular surface of the outside of the ooid is apparent, together with an amorphous crypto-crystalline body. A well rounded ovoid seed grain is visible at the centre of the ooid. The ooid lies in a fine grained calcite mud matrix. Plane polarised light.

j) This image shows a number of ovoid ooids up to 2mm in length and of the order of 1mm diameter set in a fine grained matix. The long axes of the ooids are sub-parallel and are aligned with a weak fabric apparent in the fine grained calcitic matrix, thought to represent original bedding. A variety of "seed" grains are apparent including irregular lithic fragments and an apparent pyramidal grain (pseudomorph after pyrite?). Plane polarised light.



k)



l)

k) Amongst the ooids similar to those seen previously is a further object of biological origin. This structure is also thought to be a bryozoan c.f*. Helapora fragilis* as described from coeval strata in Argentina by Halpern and Carrera (2014).An alternative assignment as a calcareous alga is also possible, in which case the potential preservation of a pair of chloroplast lie features is remarkable. Plane polarised light.

l) Close up of putative *Helapora fragilis.* Crossed polars.

Appendix 5: Geoconservation Proposals

PROPOSAL FORM FOR THE ADDITION OF A SITE TO THE GCR

PART A: SITE INFORMATION GCR SITE NO: ____________________
[To be allocated by JNCC]

1. **GCR SITE NAME: Cilborth Beach**

2. **GCR BLOCK: Caradoc-Ashgill**

3. **GCR NETWORK: Hirnantian of the Welsh Basin**

4. **GCR SITE TYPE: (Earth Science Conservation Classification) ED/EO**

5. **GRID REFERENCE: SN 311 544**

6. **COUNTRY (E, S, W): WALES**

7. **COUNTRY/DISTRICT: Ceredigion**

8. **1:50,000 OS MAP: SHEET: 194**

9. **1:10,000 OS MAP: SHEET: TBC**

10. **GCR STATEMENT OF SITE VALUE:**

a. INTRINSIC SCIENTIFIC VALUE, describing Earth science features of Special Scientific Interest:

Cilborth Beach has recently come to prominence because it has a remarkably well preserved trace fossil assemblage. The rocks are of Hirnantian (Latest Ordovician) age and are coeval with a global ice house condition, and one of the so called “Big 5” Phanerozoic Mass Extinctions. The rocks record the intra-basinal effects of the glacio-eustatic fall in sea level associated with the glaciation.

There is little if any macro-fauna allowing correlation with the coastal sediments of the day with the distinctive *Hirnantia* Fauna found at the Cwm Hirnant GCR Site near Bala. These rocks appear to be associated with the *extraordinarius* biozone. As such these strata represent the Low Stand System Tract Boundary between the glacio-eustatic regressive *anceps* / early *extrordinarius* biozones and the subsequent transgressive *persculptus* biozone. *Anceps* zone grapolites are recorded to occur in laminated hemi-pelagites further south at Traeth Penbryn, whilst the succeeding *perculptus* zone graptolites, and an occurrence of the Mottled Mudstone Member have been recoved at Traeth Pendinas Lochtyn further north.

The trace fossil assemblage is remarkable, displaying a wide variety of epichnial (top surface) trails and shallow mud-ground burrows associated with a distinctive rippled facies. The traces include representatives of trace fossils assigned to the ichnogenera *Nereites, Gordia, Merastomichnites / Diplichinites*, and *Curvolithus*, as well as some as yet undescribed and formally unnamed ichnotaxa.

b. NETWORK VALUE: How does the site relate to other sites in the GCR Block?

Cilborth Beach is a unique component of a network of only 2 further registered GCR sites (and one propsed site) relating to the Hirnantian Glacial episode. The other exsiting sites are Deganwy Quarry (GCR No 1071), and Cwm Hirnant (GCR No 1090). These two existing sites collectively provide an important palaeogeographical representation of the shelf, basin margin and basinal depositional environments of the Welsh Basin, as well as of their characteristic biotas. Both these sites have been fully documented in the CGR volume “British Cambrian to Ordovician Stratigraphy” (Rushton *et al*, 1999). Cwm Hirnant gives its name to the globally recognised Hirnantian Stage, the latest of the Ordovician, and is the type locality for two of the recognised taxa (*Eostropheodonta hirnantensis* and *Hirnantia sagittifera*) that make up the *Hirnantia* Fauna. The third site currently under review is Carn Owen.

The Cilborth Beach proposed site however gives a unique insight into the presence of an opportunistic soft body taxa that prospered during the apparent Hirnantian extinction episode. The Cilborth Beach location represents a position further west in the ocean basin than the other sites, although since it is coeval with a regression, the assumption that it represents deeper water conditions than the other GCR sites cannot be supported. The presence of rippled surfaces and evidence of tidal influence (mud drapes, Microbial Influenced Sediment Structures) suggests that the water depth may have been shallow and the oxygenation and soft body fauna are therefore associated with the acme of the glaciation.

c. INTERNATIONAL VALUE:

The Hirnantian Extinction episode identified globally amongst marine invertebrates is often stated to be the second most significant extinction episode in terms of family level and / or genus level extinctions (second only to the End Permian event, and more significant than the K/T boundary). The rocks are coeval with rocks seen at outcrop immediately below the international GSSP for the base of the Silurian (FAD P*arakidograptus acuminatus*) at Dobb’s Linn, Scottish Borders, and also the Soom Shale Lagerstatte of South Africa. The trace fossil record at Cilborth Beach records colonisation of an opportunistic soft bodied epi-benthic and shallow benthic fauna in a relatively oxic oceanic setting, associated with global changes in oceanic chemistry. The presence of a significant ichnofaunal assemblage is of profound palaeoecological significance, confirming that the supposed Hirnantian Extinction Episode did not empty the oceans of life, but allowed, at least on a local basis, a flourishing ecology to exist.

11. GCR SITE REPORT

Cilborth Beach SN 311 544
K.H. Nicholls

Introduction
Cilborth Beach has recently come to prominence because it has a remarkably well preserved trace fossil assemblage. The rocks are of Hirnantian (Latest Ordovician) age and are coeval with a global ice house condition, associated glacio-eustatic regression and one of the so called "Big 5" Phanerozoic Mass Extinction episodes. The presence of a significant trace fossil assemblage during an established mass extinction episode has profound implications for our understanding of extinction mechanisms associated with global climate change.

Site Location and Access
The site is located amongst spectacular coastal exposure on the West Coast of Wales approximately 300m north of the coastal village of Llangranog, Ceredigion. The proposed GCR site (Figure 1) comprises Cilborth Beach, and an adjacent unnamed stretch of foreshore to the north. Cilborth Beach is accessible at low tide around the "Carreg Bica" headland, and at all states of tide from a footpath and steep flight of steps off the Coastal Footpath. The adjacent stretch of foreshore immediately north of Cilborth Beach is inaccessible other than by small boat.

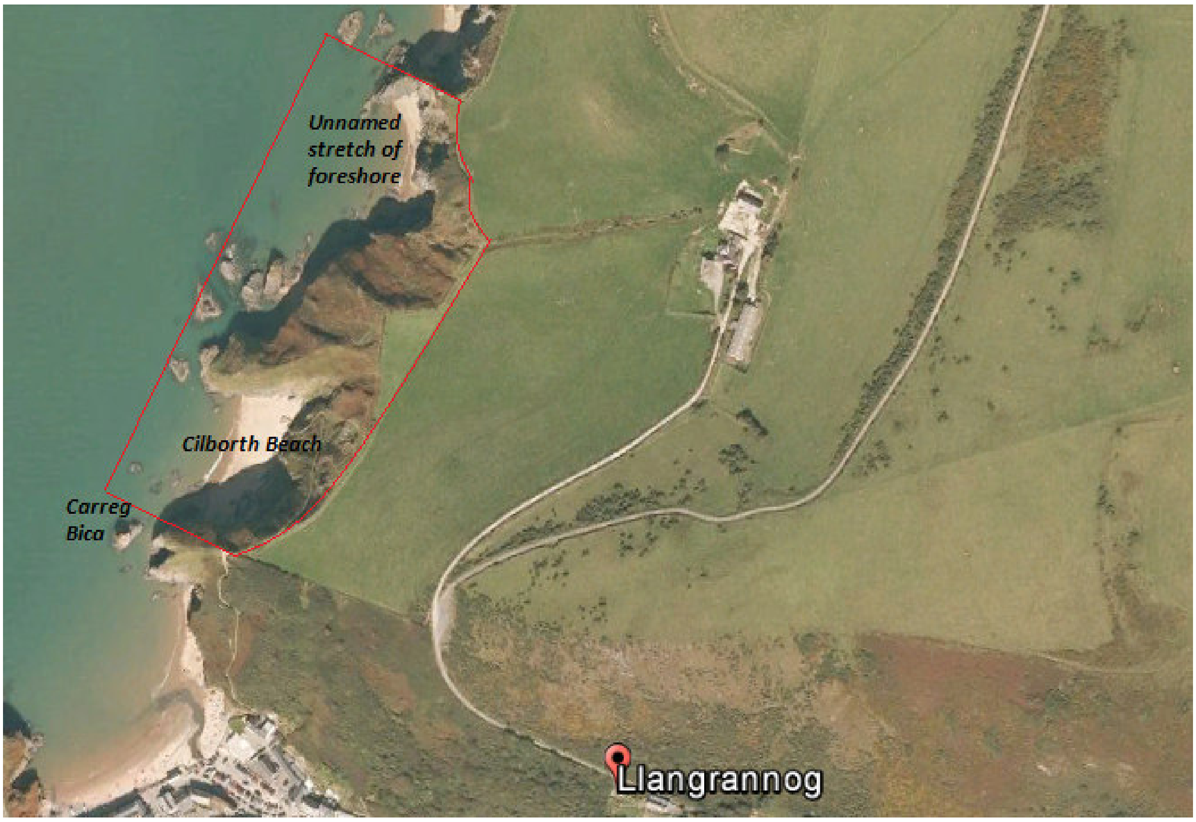


Figure 1: Proposed Boundary of Cilborth Beach GCR Site

Site Description

The trace fossils occur in a distinctive band (the "Trace Fossil Horizon") which is closely associated with a rippled siltstone / mudtone facies. Much of the surrounding rock mass however is a seemingly featureless dark grey siltstone with occasional fine sandstone stringers. The Trace Fossil Horizon itself offers approximately 1.0m of vertical section exposed in the faulted northern cliff face of the beach Figure 1. The trace fossil horizon is also exposed as a series of shallow dipping bedding plane exposures at the rear of the beach Figure 2. The north cliff face is seen to be folded into a gentle syncline with the eastern (rear) exposure compring the eastern limb of this synclinal structure. It is possible to correlate bed by bed between the northern cliff exposure and the rear beach exposure.

Figures 3, 4, 5 and 6 show typical examples of the bedding plane trace fossil assemblage present. The traces are preserved as epichnial semi-relief on bedding top surfaces, although occasionally they are seen to be overdraped with fine mudstone, implying that the traces are in fact firm ground / mudground interface burrows, with the overlying muddy substrate typically winnowed away by current action (responsible also for the appearance of the rippled facies apparent throughout the sequence). The trace fossils present include a reasonably wide ichnotaxa count, and this is considered highly unusual within the context of the global Hirnantian Mass Extinction Episode. The ichnogenera present include *Nereites, Gordia, Merastomichnites / Diplichinites,* and *Curvolithus* as well as a number of undescribed and unnamed ichnotaxa.

Whilst the traces themselves are typically not large features they are often beautifully preserved, with remarkable fine detail apparent. The traces are generally up to about 1cm in diameter and run on bedding surfaces for up to a few tens of centimeters. The *Merastomichnites / Diplichinites* traces appear to represent the largest ichnotaxon present and would appear to be associated with an animal up to 4cm in diameter, based on the typical outside distances between paired trackways.

Figure 2: Northern Cliff Face showing outcrop of the trace fossil horizon

Figure 3: Eastern (rear) of the beach (following storms with much lower sand level than normal) showing westward dipping bedding on the eastern limb of the synclinal structure

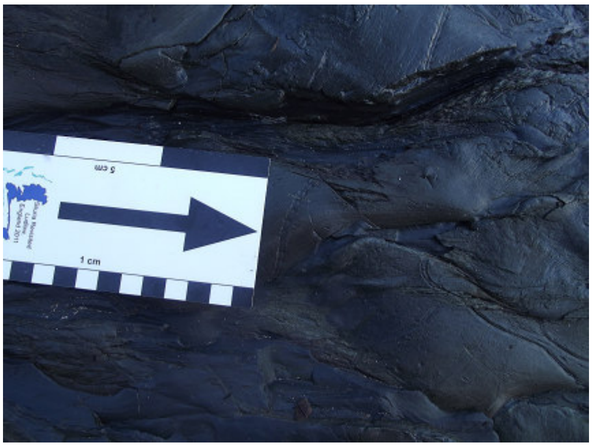


Figure 4:

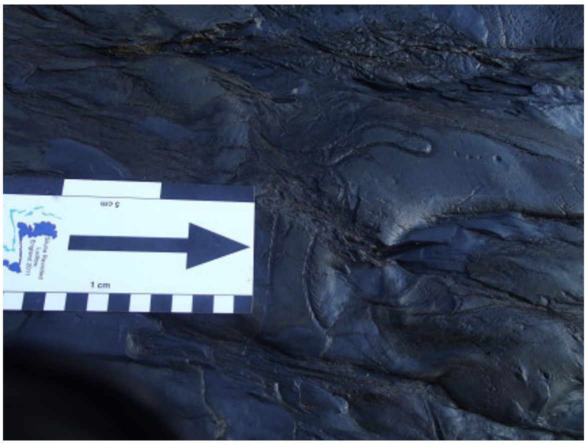


Figure 5:

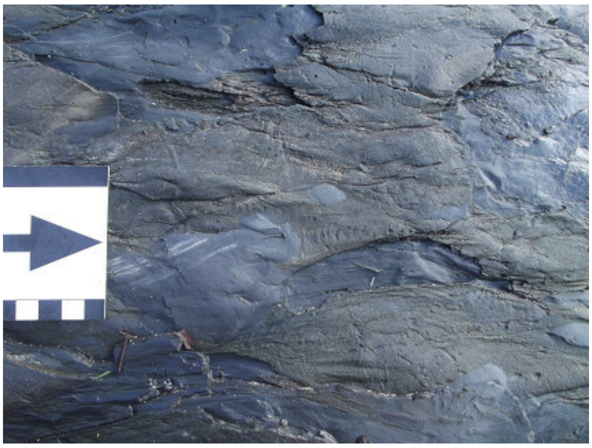


Figure 6:

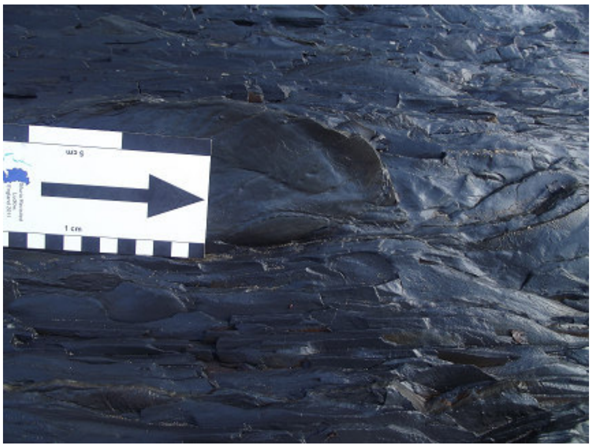


Figure 7:

Geological Context

Figure 8 below shows the position of the trace fossil horizon within the established stratigraphy of the Welsh Basin. The presence of tracks and trails within the rocks of the Llangranog district have been recorded in the literature for many years, although it has only recently become apparent as to just how remarkable the detailed preservation is, how diverse the assemblage is, and how significant it is in establishing the presence of a functioning ecosystem during a period of global mass extinction.

Previous workers to note the presence of the traces include Jones (1912) who recorded:

> *"The only other district concerning which information is forthcoming is the coast south of Llangranog. The Dicellograptus-bearing mudstones are succeeded by a considerable thickness of grey grits, these are followed by 200 to 300 feet of dark-blue, flaggy, sandy shales and mudstones, which are exposed on the steep slopes south of Traeth Bach (three quarters of a mile south-west of Llangranog). I have searched these shales for fossils, but without success. They appear to be followed conformably by dark shales with thin bands of dark-grey grits showing curious markings like annelid trails, and closely resembling in their lithological characters the beds at the base of the Aberystwyth Grits farther north."*

Between 1976 and 1979 research was undertaken at Cambridge University by Philip M Magor, and his collection is held at the Sedgwick Museum, Cambridge. This collection includes a number of trace fossils collected from the "Upper Ordovician" of the Welsh Basin. The cataloguing process has erroneously established the location of a number of his samples (WS6 and WS 8 through 12) as being from "Llangremog", whereas the original labels indicate these to be from "Llangrannog". E-mail correspondence with Phil M Magor has confirmed that his research was never written up, nor was it published (Magor 2012).

A1987 paper by Ankatell on the succession and structure in South Central Wales is notable, as in establishing a fourfold division of the Ashgill and Llandovery succession (See Tables 2.4 and 2.5) reference is made to what was termed the "Llangranog Formation" as follows:

> *"Although locally displaying a rich assemblage of trace fossils, the formation is devoid of diagnostic fauna"*(Anketell 1987).

In the revised British Regional Geology Guide to Wales (Howells 2007) the presence an undefined but apparently "*rich*" trace fossil assemblage in the "Llangranog Formation" is recorded.

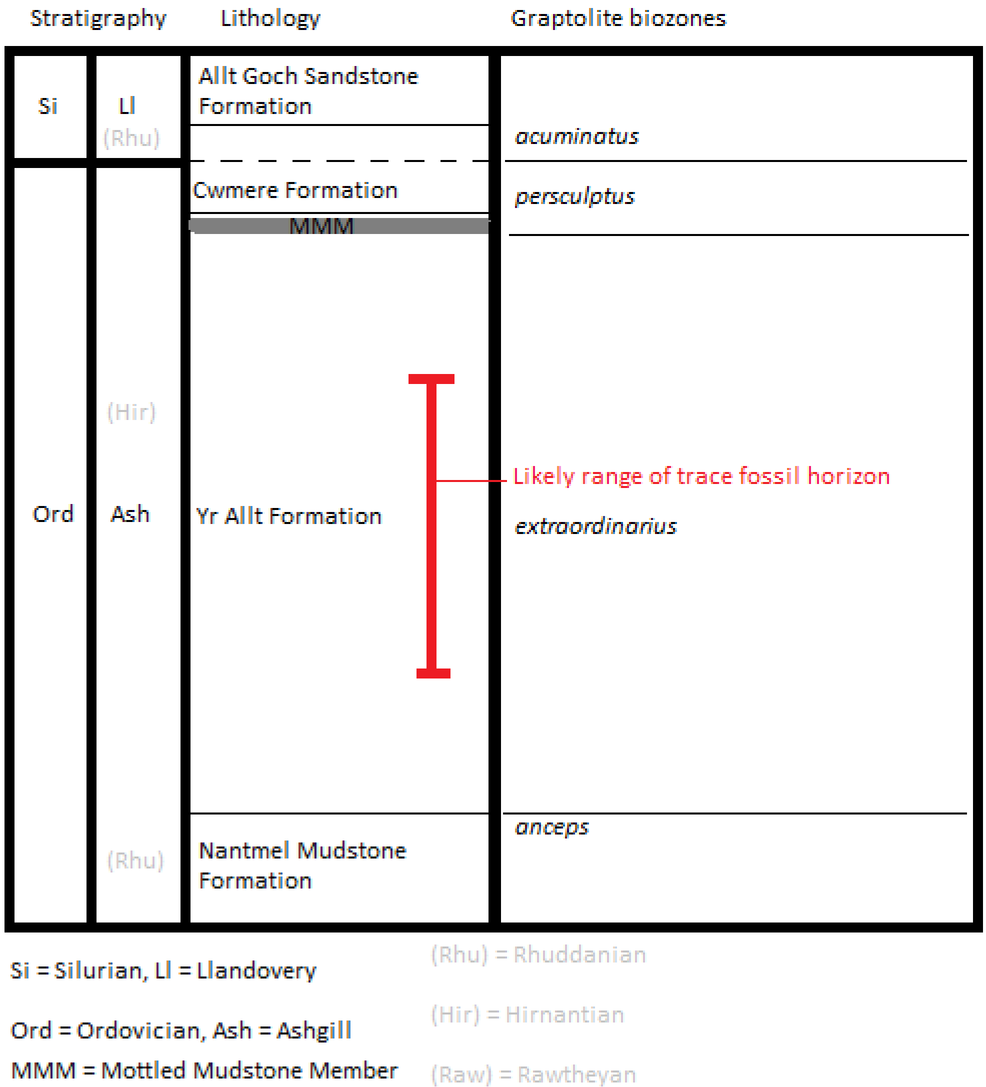


Figure 8 Summary of lithology and stratigraphy (based on Davies et al, 2006)

Interpretation

- **Interpretation:-** this should interpret the geological/geomorphological features and explain their scientific context (e.g. the mode of formation, palaeoenvironmental or palaeoclimatic reconstruction, age and relationship with other sites where the site in question is part of a wider network). The interpretation should address relevant scientific controversies (e.g. differing interpretations of palaeoenvironment, age or mechanisms of formation), in a neutral and objective manner. The site report is in effect a detached review which could have considerable longevity in the literature so it must cover changing interpretations chronologically, and set out what the currently accepted view is, and include the relevant debate. The main elements of the debate should be outlined together with suggestions for future research directed at resolving different elements of the debate. Where the site is of clear historical importance in the elucidation of geological theories and the advancement of the geological sciences, these aspects should be discussed.

Conclusion

Cilborth Beach has recently come to prominence because it has a remarkably well preserved trace fossil assemblage. The rocks are of Hirnantian (Latest Ordovician) age and are coeval with a global ice house condition, and one of the so called "Big 5" Phanerozoic Mass Extinctions. The rocks record the intra-basinal effects of the glacio-eustatic fall in sea level associated with the glaciation. The trace fossil assemblage is remarkable, displaying a wide variety of epichnial (top surface) trails and shallow mud-ground burrows associated with a distinctive rippled facies. The traces include representatives of trace fossils assigned to the ichnogenera *Nereites, Gordia, Merastomichnites / Diplichinites,* and *Curvolithus*, as well as some as yet undescribed and formally unnamed ichnotaxa.

Cilborth Beach is a unique component of a network of only 2 further registered GCR sites (and one propsed site) relating to the Hirnantian Glacial episode. The trace fossils are forming the key data set for an ongoing PhD at the University of Chester, being undertaken by the author (Keith Nicholls). On completion of this project it is anticipated that there will be significant potential for further work including detailed palaeoenvironmental studies micropalaeontology and isotope geochemistry (in determining the presence absence of the Hirnantian Isotopic Carbon Excursion (HICE).

Selected References

Anketell, J. M. (1987). "On the geological succession and structure of South–Central Wales." Geological Journal 22(S1): 155-165.

Davies, J.R., Sheppard, T.H., Waters R.A. and Wilson, D. (2006) Geology of the Llangranog District – a brief explanation of the geological map. Sheet Explanation of the British Geological Survey, 1;50,000 Sheet 194, NERC, Nottingham. 38pp

Davies, J. R., R. A. Waters, et al. (2009 (b)). "Sedimentary and faunal events revealed by a revised correlation of post-glacial Hirnantian (Late Ordovician) strata in the Welsh Basin, UK." Geological Journal 44: 322-340.

Davies, J. R., R. A. Waters, et al. (2009(a)). "A revised sedimentary and biostratigraphical architecture for the Type Llandovery and Garth areas, Central Wales: a field guide". Open Report. Nottingham, British Geological Survey: 40.

Howells, M. F. (2007). "Wales", British Regional Geology, British Geological Survey.

Jones, O. T. (1912). "The geological structure of Central Wales and the adjoining regions " Quarterly Journal of the Geological Society 68: 328-344.

Magor, P. M. (2012). Pers Comm. "On Specimens held at Sedgwick Museum". KHN.

List of Figures

12. SITE MANAGEMENT BRIEF

13. ADMINISTRATIVE STATUS

This GCR site is	1	2
identical with	☐	☐
falls within	X	☐
includes	☐	☐
largely coincides with	☐	☐
overlaps in part with	☐	☐

1. the existing GCR site named N/A_____________________

2. the existing SSSI named Aberarth-Carreg Wylan SSSI

12. PROPOSAL DETAILS

a. The proposal is supported by
Name:Prof J Davies (on behalf of the BGS)
Institute of Geography and Earth Science
Aberystwyth University
Llandinam Building
Penglais Campus
Aberystwyth
SY23 3DB

b.
Prof Cynthia Burek
Professor of Geoconservation
University of Chester
Parkside Campus
Chester

BGS commentary.

This site is proposed by: Name: Keith Nicholls

……………………….

………/………/………

Dept of Applied Biology
University of Chester

PART B: EARTH HERITAGE FORUM'S CONFIRMATION

a. This proposal has been approved by

Officer ___________________ Officer *__________________Officer* ___________

Agency ___________________ Agency __________________ Agency ___________
Originating agency

Date ______________________ Date ____________________ Date ______________

* If approval is given via postal consultation, signed a signed memo/ commentary supporting the proposal will be accepted and included with the recommendation to the Chief Scientists/ Chief Officer Panel.

b. The proposal for addition to the GCR Register has been passed to the Chief Scientist/ Chief Officer Panel under the name

____

under the unique GCR number _________________________

GCR Panel Chairperson: Name: _________________________________

Signature: ______________________________

Date: __________________________________

c. Copies of this form and corroborating information have been sent to the three agencies on Date: ____________________, and the IAESD entry for the site has been added with "Proposed" site status

North East Wales RIGS Group Site Record

Cwm Hirnant

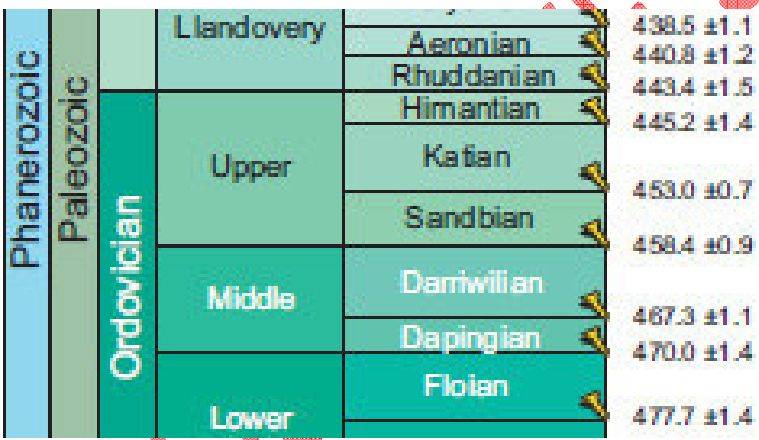
General	North East Wales
Site Name: Cwm Hirnant	File No.:
Wales RIGS Number: TBC	Surveyed by: KHN
Grid Reference: SH 952 304	Date of Visit: 16th September 2012
RIGS Category: Scientific & Historical Value	Documentation Prepared by: Keith Nicholls
Earth Science Category: Ordovician (Ashgill) Stratigraphy	Documentation last revisited:
Network: Hirnantian Stratigraphy	Photographic Record: Yes
Sub-Network: Hirnantian Glaciation	Monitoring Visit:
Unitary Authority: Denbighshire County Council	Date Registered: Prospective Site Owner: Natural Resources Wales Planning Authority: Denbighshire County Council
Site Nature: Glaciated rural upland	1;50,000 Sheet 1:25,000 Sheet

RIGS Statement of Interest:
Cwm Hirnant is of regional geological importance because of its combination of

- profound historical importance,
- the presence within the valley of the boundary between the Ordovician and Silurian Periods,
- the Quaternary glacial and fluvio-glacial features
- the well exposed relationships between cleavage, and gross geological structure

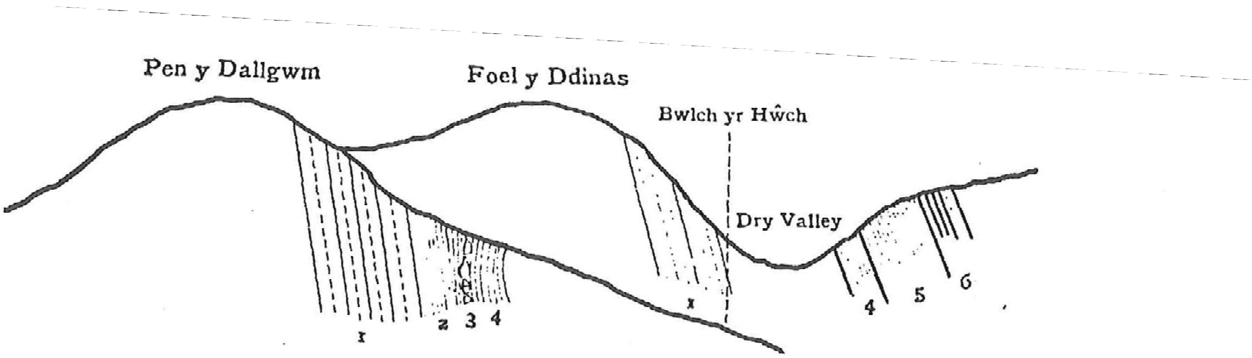
Geological setting/context:

The following is an extract from the current formally recognised geological timescale (2013):



It will be noted that the stage between 445.2Ma and 443.4Ma is known globally as the “Hirnantian”. This has arisen as a consequence of the description of two key brachiopods *Hirnantia sagittifera* and *Eostropheodonta hirnantensis* from the Chwarel Cwm Hirnant SSSI located at the south western edge of the proposed RIGS. These are two key taxa which form part of the globally recognised “Hirnantia Fauna” – a collection of cold adapted specialists that lived in the oceans around low and mid Southern Hemisphere latitudes during the short lived Hirnantian Glaciation of the Gondwana continent. This was the first major glaciation of the Phanerozoic Era, and was coeval with what is generally accepted as the second most profound global mass extinction event, since multi-cellular life appeared at the start of the Cambrian.

The area has been the subject of detailed geological research over many years, and continues to attract researches from far afield. The following figure is an extract from a classic paper on the Geology of the Bala District by Gertrude Elles:



1=Foel-y-Ddinas Beds.
2=Hirnant Mudstones below Hirnant Limestone.
3=Hirnant Limestone.
4=Hirnant Mudstones above Hirnant Limestone.
5 & 6=Graptolitic shales yielding graptolites indicative of the zones of *Monograptus sedgwicki* and *M. crispus*.

The image used on the front of this description shows Foel y Ddinas and the Dry Valley noted above, with Bwlch yr Hwch in the foreground. The image is taken from a location on the flanks of Pen y Dallgwm just above the outcrop of the Hirnant Limestone shown, above the location of the SSSI.

The presence of the Hirnantian Hirnant Mudstone (now generally known as the Foel y Ddinas Mudstone) below the Llandovery graptolitic shales with *Monograptus sedgwicki* and *Monograptus crispus* reveals the presence of the Ordovician / Silurian boundary at this location. Isolated fragments of the Hirnantia Fauna can be found in and around the Dry Valley.

Recent work in the area has included studies of the acritarch fossils in the mudstones, and there is ongoing work on the detailed geochemistry. There is much still to be determined in these sections including:

- the establishment of the direction of dip of the strata exposed in the SSSI site (in the quarry and immediate surroundings the rocks dip to the west, despite their presence on the supposed eastward dipping flank of the Llandderfel Syncline),
- the absence / presence of the Hirnantian Isotopic Carbon Excursion and
- the nature of the Ordovician / Silurian boundary,

References:

Elles GL, (1922) The Bala Country: Its Structure and Rock-Succession, QJGSoL, Vol 78

Bassett DA, Whittington HB & Williams A (1966) The stratigraphy of the Bala District, Merionethshire, QJGSoL, Vol 122

Temple JT, (1965) Upper Ordovician brachiopods from Poland and Britain, Acta Palaeotologica Polonica, Vol X No 3

Vandenbrouke, TRA et al (2008) New chitinozoans from the historical type area of the Hirnantian Stage and additional key sections in the Wye Valley, Wales, UK, Geological Journal, Vol 43

PRACTICAL CONSIDERATIONS:

Accessibility:

There is a small amount of car parking space available at the bridge crossing of the Afon Hirnant. Buses etc can turn around at this location but should park further north in the Aberhirnant Car Park.

There are no public toilets in the vicinity and visitors should be self sufficient in food, water and clothing. The nearest shops and public conveniences are in Bala.

Safety:

Whilst the site is only a short distance from the A5 trunk road,the site should be considered remote, as it is not visited frequently. Mobile telephone reception is poor.

Conservation Status: TBC

OWNERSHIP/PLANNING CONTROL:

Much of the site lies within areas of forestry managed by Natural Resources Wales. The area of open farmland are tenanted from Maesafallen. Large groups should obtain permission before visiting the SSSI site

Planning Authority: Denbighshire County Council

Planning Status / Constraints: TBC

CONDITION, USE & MANAGEMENT:

Present Use: Sheep grazing, forestry

Site Condition: Mixed open farmland and Forestry

Potential Threats: Uncontrolled quarrying could have a devasting impact at the O/S boundary interval. (considerable scientific potential from controlled excavation in the Dry Valley area)

Site Management:

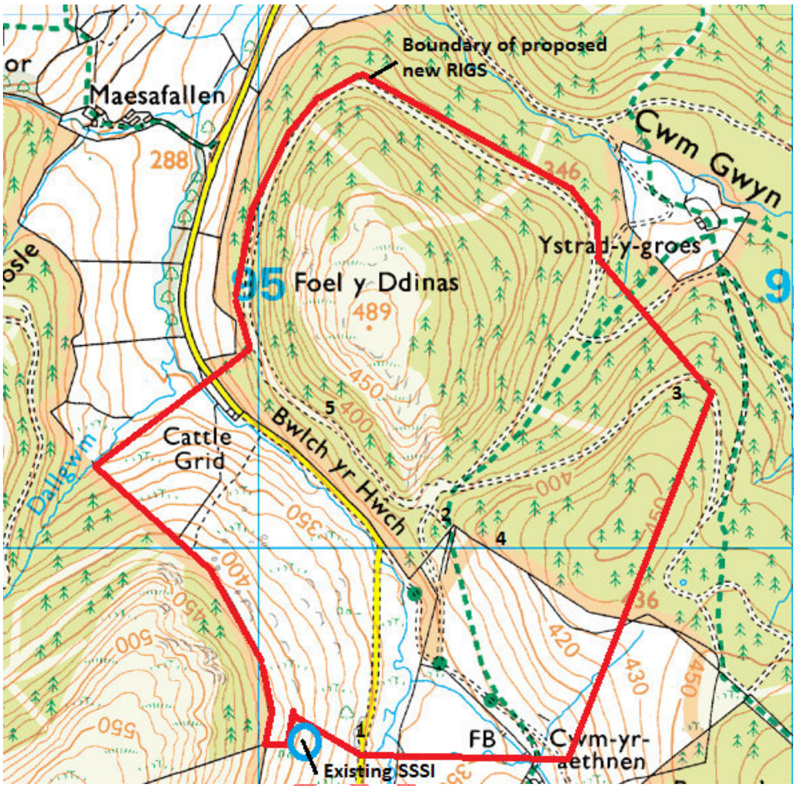
Monitoring Visits

SITE DEVELOPMENT:

Potential Use (General)

Potential Use (Scientific Educational)

Map



Numbers show the locations of images in Photographic record

Aerial

Photographic Record:

Exposure of glacial outwash and overlying post Glacial Peat being eroded by Afon Hirnant (Location 1)

Brachiopods and graptolites found amongst loose debris from the Dry Valley near Bwlch yr Hwch (Location No 2)The larger of the two brachiopods on the first image is *Hirnantia sagittifera.*

Llandovery (or Wenlock?) turbidite sandstones in quarry / borrow pit at Location 3 (note near vertical cleavage in mudstones)

Graptolite recovered from insitu exposure at Location No 4

Weathering eroding dip / scarp topography on the southern flank of Foel y Ddinas (beds dipping east)

Gwynedd RIGS Group Site Record

Coed Tal-y Llyn, Llanrwst

General	Gwynedd & Mon RIGS
Site Name: Coed Tal-y-llyn	File No.:
Wales RIGS Number: TBC	Surveyed by: KHN accompanied by Peter Appleton and others
Grid Reference: SH755591	Date of Visit: 11th November 2014
RIGS Category: Scientific	Documentation Prepared by: Keith Nicholls on behalf of NEWRIGS
Earth Science Category: Ordovician stratigraphy (Caradoc) and Mineralogy	Documentation last revisited:
Network:	Photographic Record: Yes
Sub-Network:	Monitoring Visit:
Unitary Authority: Conwy County Council	Date Registered: Prospective Site Owner: Natural Resources Wales Planning Authority: Snowdonia National Park?
Site Nature: Borrow Area adjacent to Forestry Haul Roads	1;50,000 Sheet 1:25,000 Sheet SH75

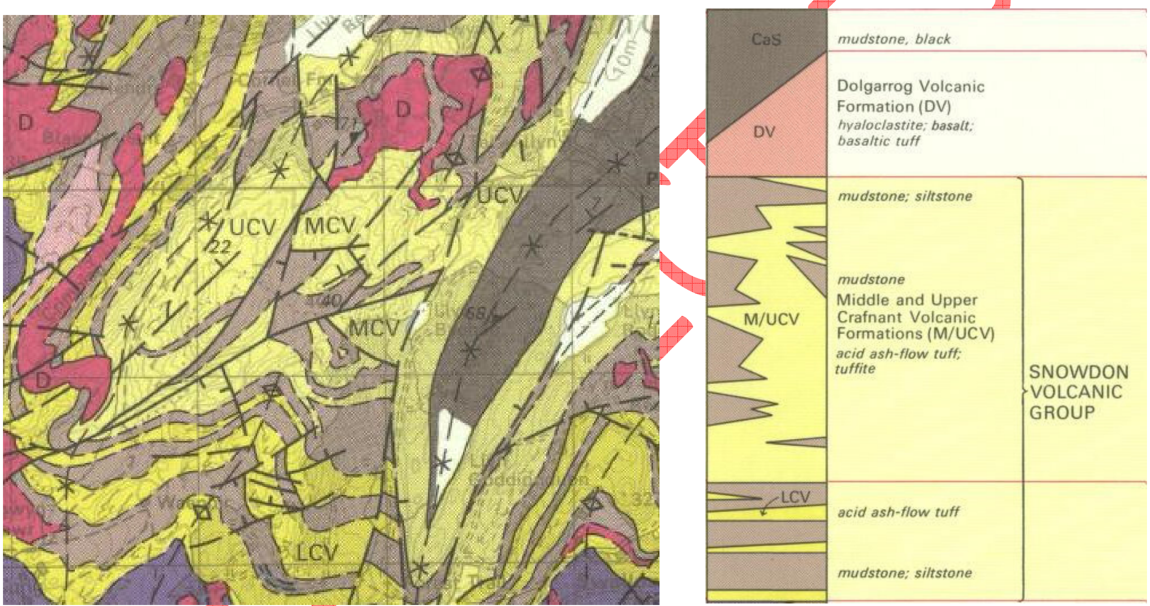
RIGS Statement of Interest:

Coed Tal-y-llyn is of regional geological importance on two accounts:

1. The site shows significant primary sulphide mineralisation (pyrite) in a deep water sequence of shales and mudstones, and is representative of "black smoker" type volcanism in a marine setting.

2. There are prodigious quantities of graptolite fossils preserved on bedding planes in quite extraordinary quantities. The assemblage appears to be a monospecific – and presumably records one or more "mass mortality" events. The possible occurrence of graptolite flotation devices (still under review) would be of profound palaeontological significance.

Geological setting/context:



Contains British Geological Survey materials © NERC [1985].

The borrow pit has been excavated in the Cadnant Shale (the dark grey on the map and section). Graptolites are encountered in what appears to be a monospecific assemblage preserved locally in prodigious quantities.

Unfortunately the preservation of the stipes themselves is not very detailed, making identification, beyond noting them to be consistent with biserial orthograptids at generic level, extremely difficult.

The Cadnant Shales are the local name for the Nod Glas Horizon, an anoxic marker present throughout much of mid Wales, and associated with the Cheneyan and Streffordian Stages of the mid to late Caradoc. These rocks are associated with the *clingani* graptolite stage (Fortey et al, 2000). Graptolites that could be expected within rocks of this age include *Orthograptus calcuratus, Orthograptus truncatus, Climacograptus bicornis* and *Amplexograptus perexcavatus* (Howells et al, 1978).

Pyritic nodules, some approaching the size of an egg, are plentiful, with many showing tufts of quartz. It seems probable that the pyrite nodules (or concretions) were formed as part of the original lithification process; and by the time of the Caledonian Orogeny, which imposed the slaty cleavage of the district on the shales, the nodules were already significantly stronger than the surrounding host rock.

As well as the concretionary nodules the pyrite was also seen to be associated with particular bedding horizons. This is consistent with descriptions of mineralisation as a “stratified pyrite deposit” in the same rocks near Dolgarrog (Howells, 2007). Reference to the geological section above shows the close association between the mudstone and the basaltic Dolgarrog Volcanic Formation. The sulphide mineralisation seen at the quarry is thought to be primary mineralisation, associated with sea floor hydrothermal volcanism of “black smoker” type. Much of the mineralisation in the surrounding metalliferous ore field of course is quite different, being of a secondary origin, formed by remobilised minerals, presumably originating from primary sources such as this.

References:

Fortey R. et al (2000) A revised correlation of Ordovician rocks in the British Isles, Geological Society Special Report No 24, London.

Howells M., Francis E., Leveridge B. and Evans C. (1978) Capel Curig and Betws-y-coed, Description of 1:25,000 Sheet SH75, Classical Area of British Geology, IGS, NERC, London

Howells M. (2007) Wales, British Regional Geology, BGS, Nottingham.

PRACTICAL CONSIDERATIONS:

Accessibility: Car Parking and public toilets available at Llyn Geirionydd. Access is possible on foot from there approximately 25 mins walk (mostly uphill) on Forest Tracks.

Safety: Forestry haul roads, stored cut logs, underfoot conditions locally slippery and uneven.

Conservation Status: TBC

OWNERSHIP/PLANNING CONTROL:

Owner Natural Resources Wales: Open Public Access on foot

Planning Authority: Snowdonia National Park?

Planning Status / Constraints: TBC

CONDITION, USE & MANAGEMENT:

Present Use: Borrow pit being used to provide bulk fill for haul road construction for logging operations

Site Condition: Open quarry type borrow pit in Gwydir Forest.

Potential Threats: Continued uncontrolled excavation. Uncontrolled fossil and mineral collecting

Site Management:

Monitoring Visits:

SITE DEVELOPMENT:

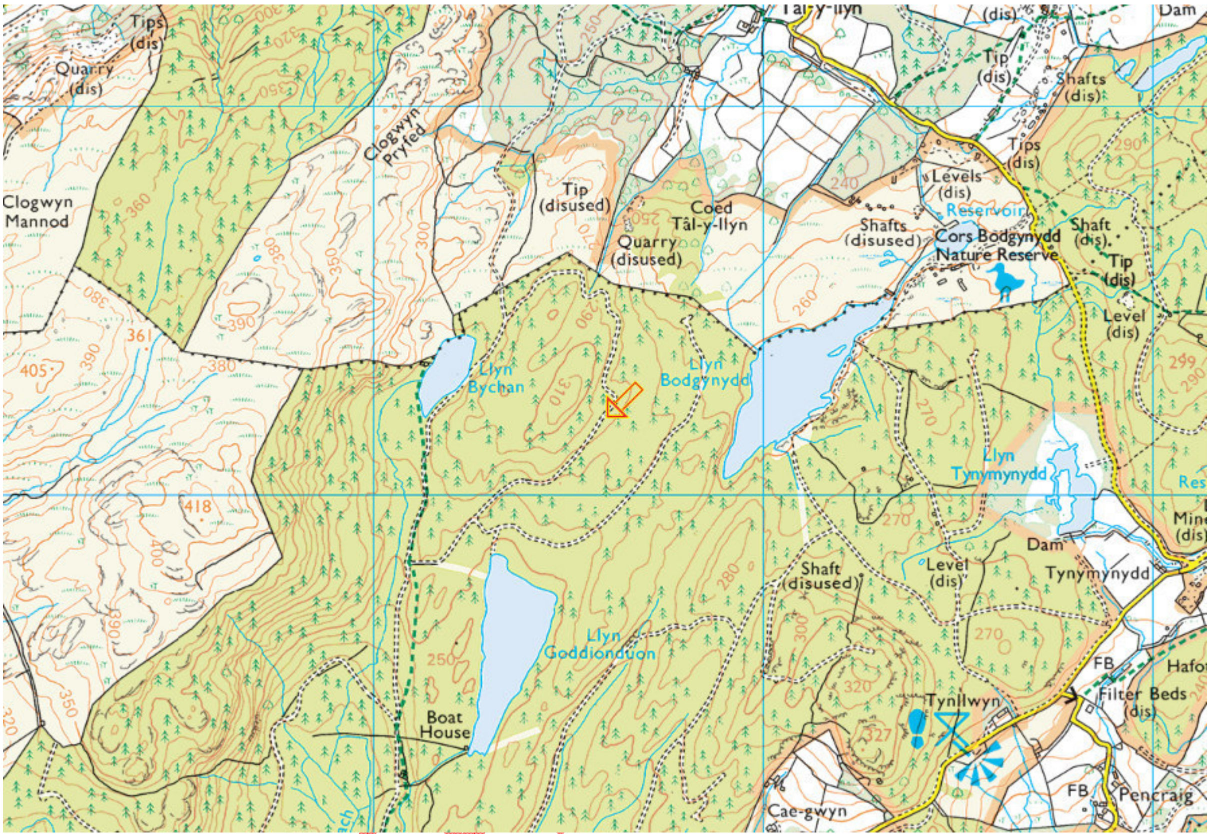
Potential Use (General)

Provides substantial opportunity for further research into Ordovician palaeo-ecology, graptolite mortality events, and the primary mineralisation of the regional sulphide Orefield

Potential Use (Educational)

Excellent three dimensional exposure illustrating good structural geology (folding and cleavage development) as well as relationship between tuffaceous sediments and marine sediments.

Map



Tips (dis)
Quarry (dis)
Clogwyn Mannod
Clogwyn Pryfed
Tip (disused)
Coed Tâl-y-llyn
Quarry (disused)
Shafts (disused)
Levels (dis)
Reservoir
Cors Bodgynydd Nature Reserve
Shaft (dis)
Tip (dis)
Level (dis)
Tips (dis)
Tip (dis)
Shafts (dis)
Dam
Llyn Bychan
Llyn Bodgynydd
Llyn Tynymynydd
Dam
Tynymynydd
Shaft (disused)
Level (dis)
Llyn Goddionduon
Boat House
Tynllwyn
FB
Filter Beds (dis)
FB
Pencraig
Cae-gwyn

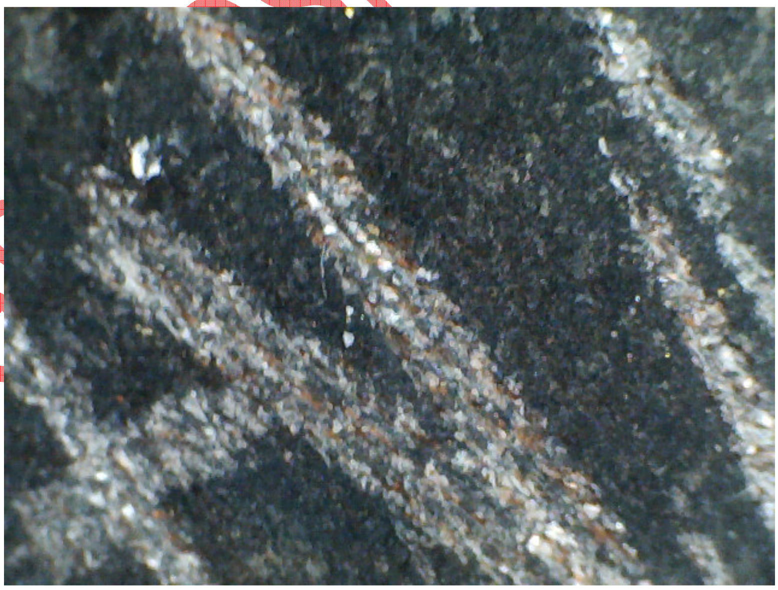
Aerial

Llyn Bodgynydd
© 2015 Google
Google earth

Photographic Record:

Graptolites on bedding planes with potential flotation device apparent

Graptolites in prodigious quantities preserved on bedding plane with two further potential flotation devices (**fd i** and **fd ii**)



Close up image of graptolites – diameter of specimens typically about 1mm

Concretionary nodule of pyrite with quartz strain shadow mineralisation


Small pyrite nodules with aligned quartz overgrowths